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Final Report On Research and Development of Titanium Rocket Motor Case Volume II - Ring-Rolling and Flow-Turning Cylindrical Sections

Written by:

Approved by:

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FOREWORD

This final technical report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation in compliance with Army Contract No. DA-19-020-ORD-5230. It covers technical accomplishments on a program of research and development of titanium rocket motor cases sponsored by the Army Materials Research Agency, Watertown Arsenal, Watertown, Massachusetts, under the technical supervision of Mr. S. V. Arnold.

ABSTRACT

Prior to this program, Pratt & Whitney Aircraft fabricated 40-inch diameter rocket motor cases from B-120 VCA titanium alloy and formed the center sections of these cases by flow-turning. Although these cylinders had adequate strength properties and satisfactory hydrotest performance, dimensional control during flow-turning was inadequate to meet the required tolerances. A large amount of diametral growth and local bulging occurred during flow turning. The subject program was undertaken to develop a flow-turning practice to produce cylinders which would meet the dimensional as well as improved strength requirements.

The ring rolling technique and heat treatment used before flow-turning were investigated to improve the quality of the flow turning blanks. A solution treatment was developed which considerably improved the ductility and structure of the starting blanks.

A major improvement in flow-turning technique was developed with subscale parts. The effects of roller geometry, mandrel speed, wall thickness reduction per pass, and roller-feed rate on radial growth and local bulging were determined. It was found that roller geometry had the most predominant effect on dimensional control and a new roller design with parabolic contours was developed which gave positive control of diametral growth. A correlation of flow-turning parameters was developed which permitted techniques developed with subscale cylinders to be directly applied to full scale parts. The resulting full scale flow-turned cylinders had very little diametral growth and no local bulging.

In addition to the improvement in dimensional control, processing of the flow-turned cylinders was investigated to improve material properties. A stress relief treatment was developed which gave 50 to 60 per cent reduction in residual stress. Sizing of the cylinders was accomplished after stress relief and was followed by aging to the desired strength level. Cylinders fabricated by the developed techniques were capable of being aged to a minimum circumferential yield strength of 200,000 psi with 4 per cent minimum elongation and adequate toughness.

Burst testing has demonstrated that flow-turned cylinders processed by the techniques developed (minimum circumferential yield strength of 200,000 psi) exhibit excellent performance under hydrostatic loading. Results are completely described in Volume IV, Fabrication and Testing of Full Scale Components.

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I. INTRODUCTION

A. Purpose and Scope of Project

As a part of the early development of the Pershing missile, a supporting program was conducted to determine the suitability of beta titanium alloy Ti - 13% V - 11% Cr - 3% Al (B-120 VCA) for rocket motor case applications. The work was performed under U.S. Army Contract No. DA-01-009-ORD-634, subcontract RM-962, and included the fabrication and testing of several subscale and full scale cases. The excellent results obtained indicated that additional research and development with this alloy would be justified.

In 1960, the United States Army Materials Research Agency, which was assigned responsibility by the Department of Defense for conducting the Solid Propellant Rocket Motor Materials Program, awarded the present contract to Pratt & Whitney Aircraft to develop production processes for general rocket motor case applications of the beta alloy. Although cases were made to the design established for the second stage of the Pershing missile, this was a matter of economy dictated by the availability of tooling and emphasis was placed on improving the state of the art toward possible future Department of Defense requirements rather than on specific motor case applications.

B. Background

Forty-inch diameter rocket motor case center sections were flow-turned under the RM-962 contract.

Although these cylinders had adequate strength properties and performed satisfactorily both during hydrotesting and during the static firing tests of full scale rocket motor cases, dimensional control during flow-turning was inadequate to meet the required tolerances. During the first of two flow-turning passes, a diametral growth of as much as 0.300 inch occurred. Before being given the second pass the cylinders had to be sized. Sizing was performed in a hydraulically operated machine which employed

a tapered ram to force a segmented cluster assembly against the outside surface of the cylinder and thereby reduce the diameter. The second pass produced diametral growth and also local bulging. Although a limited amount of diametral growth could be corrected by the sizing operation, bulging could not be easily corrected. Further, the flow-turning procedure used produced a non-uniformly worked structure in the cross-section of the cylinder wall. The current program directed attention toward developing a flow-turning procedure to produce material which would meet the dimensional as well as the improved strength requirements.

One of the outstanding features of a B-120 VCA titanium alloy as a rocket motor case material is its corrosion resistance. Pressure vessels of this material need no protective coating to prevent pitting or general oxidation. This was demonstrated in the RM-962 program by storing a pressure vessel containing a flow-turned cylinder aged to the 180,000 psi yield strength level with a single girth weld (not stress-relieved) in a salt-spray humidity cabinet at 125F for 134 days. Radiographic, fluorescent penetrant, "Dye-Chek", and visual inspection revealed no cracking, pitting or other evidence of corrosion. Because of this test, a program to investigate the corrosion resistance of flow-turned material was not undertaken. No corrosion or stress-corrosion problems were encountered during the subject contract.

Stress corrosion susceptibility of forged material and sheet weldments were also investigated under the subject contract. Specimens from press-forged pancakes with oxygen contents ranging from 0.10 to 0.20 per cent were stressed in tension to 50 per cent of the yield strength or 90,000 psi and subsequently exposed to a salt spray without detrimental effects. Similarly, weldments were prestrained by bending and exposed to the salt spray, also without detrimental effects. These tests are discussed in Volumes I and III of this report.

Stress-corrosion cracking of material in the as-flow-turned condition has been encountered previously, but not in the subject program. Such cracking results from the combined effects of contaminants, such as halides, and the high residual stresses (up to 200,000 psi) present in as-flow-turned material. Careful handling and prompt stress relieving at 850F has prevented cylinder cracking in the subject program.

II EVALUATION OF MATERIAL FLOW-TURNED UNDER CONTRACT RM 962

A. Preferred Orientation of Flow-Turned Material

X-ray diffraction studies of flow-turned material were conducted to determine the directional properties and the nature of the deformation in flow-turned material. Two 0.35-inch laminated cubes were prepared from a 40-inch diameter cylinder which had been flow-turned by a two-pass technique (50 per cent reduction each pass) and aged at 850F for one-half hour. One cube contained laminations taken from the outside surface and the other contained laminations from the inside surface. Additional 0.350-inch laminated cubes were prepared from annealed and from cold rolled (50 per cent reduction) and aged (850F(1/2)AC) 0.062-inch thick sheet stock utilizing the entire sheet thickness. The cubes were sectioned to produce a diagonal face making equal angles with the three orthogonal faces. The surface was then polished metallographically and lightly etched. The specimen was installed in a Norelco motor-driven goniometer with conventional Schultz geometry so as to trace a spiral through the stereo-graphic projection, using the diagonal face of the specimen as the reflecting surface. The reflected X-ray beam intensities were sensed by a Geiger counter and continuously recorded on a strip chart. At discrete time intervals base-line reflected intensities were obtained from a sample with a random crystal orientation placed at the same position as the specimen. The ratio of the intensities of reflected radiation from the two samples were plotted on the quadrant of the pole figure and boundaries were drawn around areas with similar intensity ratios. Because of the specimen geometry used, only a single run was required to determine the complete quadrant of the pole figure. The frequency of data points and the method of presentation are shown in Figure 1. The reference direction is parallel to the axial direction of the flow-turned cylinder or parallel to the sheet rolling direction.

The intensity distribution of the reflections from $\{110\}$ planes was obtained using filtered copper radiation. The data from the four types of specimens (annealed and cold rolled sheet, and outer and inner surfaces of flow-turned material) are presented in the form of $\{110\}$ pole figures in Figures 2, 3, 4 and 5 respectively. With the exception of material in the mill-annealed condition, all of the samples exhibited distinct textures. The

data from mill-annealed material (Figure 2) shows a slight indication of a (100) [011] texture, but is otherwise close to random. For the deformed material, the preferred orientations which are nearest to the ideal, that is, the cystallographic planes and directions which lie parallel to the deformation direction, are indicated on each of the pole figures (Figures 3 through 5). The textures are summarized in Table I and illustrated schematically in Figure 6.

As indicated in Table I, X-ray diffraction analysis has determined that flow-turned B-120 VCA titanium alloy exhibits two distinct texture components, namely, (100) [011] and (111) [11$\bar{2}$] . Only the (111) [11$\bar{2}$] is present at the outside surface, but both components are present at the inside surface. Since the (111) [11$\bar{2}$] component conforms upon rotation through 90 degrees to the (111) [1$\bar{1}$0] component found in the cold-rolled samples, it appears that the principal working direction is circumferential even though the flow-turning operation results in elongation of the material without any change in the inside diameter. That the circumferential direction is the principal working direction is further substantiated by tensile testing which indicated higher strengths and faster aging response for circumferentially oriented specimens than for axially oriented specimens (Table II). The mixture of textures at the inner surface, however, indicates that metal in contact with the roller flows spirally to a depth of at least 0.015 inch while the metal adjacent to the mandrel flows in an axial direction. The extent of these directional deformities depends on the flow-turning parameters.

B. Fracture Toughness Test Methods

It was necessary to determine the fracture toughness of B-120 VCA titanium alloy as a function of yield strength in order to make the most efficient use of the material. It was also desired to determine if more economical tests such as the modified Charpy impact and instrumented-bend tests could be correlated to fracture toughness tests using the standard ASTM 3 by 12-inch G_c specimens. The effect of G_c specimen size on fracture toughness values was also investigated.

Initially, material was used from 40-inch diameter cylinders numbers 1 and 2 from the previous program (contract RM 962).

These cylinders had been flow-turned with a reduction of about 50 per cent on the last pass to a wall thickness of 0.080 inch. They were subsequently stress relieved at 850F for one-half hour and sectioned into axial and circumferential specimen blanks. These were aged at 800F for various times and machined into standard ASTM 3 by 12-inch internally notched fracture toughness specimens (see Figure 7) and into smooth tensile specimens with a one-inch gage length (Figure 8). Circumferential specimens were flattened by clamping during the 800F aging treatment. Slow crack growth was measured by the ink stain technique.

The results from testing these specimens appear in Table III and indicate that for circumferential specimens the toughness is lower and the yield strength higher than for axial specimens. The results also showed that the two cylinders had equivalent toughness levels. As shown in Figure 9, a close correlation was found between fracture toughness and yield strength. The toughness (G_c) at the 200,000 psi yield strength level is approximately 225 in-lbs/in^2. Although this value is low, it is believed to be an adequate combination of yield strength and toughness since only very slight defects have been encountered in flow-turned cylinders. Cylinders flow-turned and aged to the 200,000 psi yield strength level and pressure tested have burst at the estimated biaxial ultimate tensile strength of the material. Further, the fracture surfaces exhibited 100 per cent shear-type failures which verifies that the toughness level obtained is adequate for flow-turned material without detectable defects (see Volume IV of this report for a complete discussion of flow-turned cylinder burst testing and analysis).

Additional testing was conducted to determine the effect of specimen size on fracture toughness. The specimens employed were an internally notched ASTM 3 by 12-inch standard specimen, a 2 by 8-inch externally notched specimen (Figure 10), and a 1 by 4-inch externally notched specimen (Figure 11). All specimens were 0.080 inch thick. The results of testing these specimens appear in Table IV and indicate that toughness values decrease with decreasing specimen size.

Modified Charpy impact specimens were machined in the axial and circumferential directions from flow-turned cylinders numbers 1 and 2 and aged to various yield strength levels. The specimen configuration used is shown in Figure 12. These specimens were tested at -35, 70, 215, and 400F and results appear in Table V. As shown in Figure 13, at a given yield

strength level and direction, the energy absorptions decrease with decreasing test temperature. The transition temperature for this material tested by this technique was apparently near or above 400F. At a given test temperature, the energy absorption decreased with increasing yield strength regardless of direction (see Figures 14 and 15). This trend is readily apparent at 400F, less evident at 215F, and barely discernible at 70 and -35F. The correlation of energy absorption with yield strength at 400F is similar to that observed with G_c test results (Figures 9 and 14). Although the use of modified Charpy impact specimens resulted in values which were comparable to those determined using standard specimens, the scatter in the results, resulting either from material variations or from the difficulties of accurate energy measurement, was considered excessive for reliable correlation and investigation of this testing method was discontinued.

Instrumented-bend specimens (1.50 x 0.875 inch) were machined from cylinders numbers 1 and 2 and tested at various yield strength levels. The results are shown in Table VI. Some correlation with yield strength was observed, but the correlation is not as distinct as that obtained with G_c testing. Similar to the results obtained using the modified Charpy impact test, the scatter in the data obtained from instrumented-bend testing was too great for reliable data analysis and investigation of this testing method was also discontinued. All subsequent fracture toughness tests employed standard 3-inch wide internally notched specimens.

III RING ROLLING

Experience gained during the program conducted under contract RM-962 on flow-turn blanks which had been roll forged at 1850F in from 3 to 12 operations and sized at 1400F indicated that frequently the resulting flow-turned cylinders exhibited intergranular separations on the inside surfaces. In one instance this condition caused catastrophic failure during flow-turning. These difficulties were believed to result from a grain boundary precipitate which formed during ring rolling. A program was therefore conducted to eliminate the difficulty and to optimize the ring rolling practice to produce high quality flow-turn blanks of B-120 VCA titanium alloy.

Initial investigation was conducted on 14-inch diameter rings and the most promising technique developed was subsequently applied to 40-inch diameter rings.

A. Subscale 14-Inch Diameter Rings

Forging Techniques and Mechanical Property Evaluation - Material for the 14-inch diameter subscale ring rolling program was obtained from the bottom half of an ingot having the following composition (in per cent):

V	Cr	Al	Fe	C	H	O	Ti
13.69	11.74	3.41	0.28	0.0183	0.003	0.11	balance

Six blanks for ring rolling were extruded in single operations. The first three of these were subsequently rolled in single operations at 2000, 1900, and 1800F respectively. The remaining three were rolled in multiple operations at temperatures from 1800 to 2000F (see Table VII). Test pieces were trimmed from the first three rings and annealed at 1450F for 30 minutes followed by a water quench. (The selection of this annealing treatment was based on results from previous investigations conducted over the temperature range of 1450 to 1750F. No recrystallization or grain growth was noted after any of the treatments and therefore for convenience the lowest temperature investigated was selected). These specimens were tested with the results (Table VIII) indicating satisfactory ductility and notched toughness for flow-turning All six rings were therefore annealed and sized as required at 1450F and water quenched. After annealing, all of the rings

exhibited coarse, equiaxed microstructures such as shown in Figure 16.

Test hoops were trimmed from one end of rings numbers 4, 5, and 6. Additional material for test specimens was trepanned from the inside surface of each ring at the end opposite that from which test hoops had been removed. Smooth and notched ($K_t = 8$) tensile testing was conducted and the results (Tables IX and X) further demonstrate the adequate ductility and notched ($K_t = 8$) toughness of the rings and also show that all six rings were uniform and had equivalent properties.

Smooth tensile specimens were machined from rings numbers 1, 2, and 3 and aged at 900F for various times. The results of testing these specimens (Table XI and Figure 17) show that these rings had equivalent aging responses and generally low elongations. These results demonstrate that rings forged at differing temperatures have equivalent properties after being annealed at 1450F.

The results of the subscale ring rolling program have indicated that the properties of annealed (1450F (1/2) WQ) flow-turn blanks are independent of forging practice within the range of techniques investigated. On the basis of this study, a temperature of 1900F (the temperature of the soaking furnace) was chosen for forging future roll-forged rings. Ten additional 14-inch diameter rings were roll-forged for the subscale flow-turning development (see Table XII). The first seven of these rings were forged in a single operation at 1900F, but tooling difficulties (resulting in finning during the forging of the last three rings) required a second forging operation. The tensile properties of the ten additional rings appear in Table XIII and indicate lower ductilities than observed previously (Table IX and X).

Metallographic Investigation of Effect of Heat Treatments on Microstructure - Grain boundary constituents were occasionally observed in the microstructures of the 14-inch diameter flow-turn blanks. Similar grain boundary conditions had previously been observed in roll-forged rings produced under contract RM 962. These observations led to an investigation of the precipitation characteristics of the subject alloy since it was believed that,

although the 14-inch diameter flow-turn blanks had considerable ductility, the elimination of the constituent would increase the ductility and permit a more severe flow-turning technique. The use of increased reduction, feed, and roller radius would improve the inside surface condition of the flow-turned cylinders.

Samples of a 40-inch diameter roll-forged ring, 0.250-inch thick plate-stock, and a particularly poor 5-inch diameter forged blank were used for these studies. The 40-inch diameter ring was one of two transferred from the previous program and had been successfully flow-turned for use in studying the effects of hydrogen. The 5-inch diameter blank received multiple forging upsets at approximately 2000F and subsequently ruptured during flow-turning. The plate-stock was used for comparison purposes and also because it exhibited a grain boundary constituent in the mill-annealed condition.

Samples of the above materials were first heated for two hours in an argon atmosphere at temperatures in the 900 to 2100F range and water-quenched. These treatments were intended to determine the temperature range or ranges in which grain boundary and matrix precipitation occurred and to determine in what ranges these constituents could be placed in solution. Micro-examination of the specimens after treatment showed the following:

1. In the 900 to 1200F temperature range, matrix and grain boundary precipitation occurred in all samples with the constituent particle size and spacing increasing with increasing temperature. The particle shape was acicular when formed between 900 and 1200F, which is characteristic of alpha phase. Samples of the 40-inch diameter ring heated at 1200F showed a structure very similar to the poor 5-inch diameter blank in the as-forged condition (see Figures 18 and 19).

2. In the 1300 to 1400F temperature range, a small amount of both grain boundary and matrix precipitate was observed in the relatively clean 40-inch diameter ring and plate stock (see Figures 19 and 20). The 5-inch diameter blank showed a smaller amount of constituent

than in the as-forged condition indicating that some re-solution had occurred (Figure 18). The nature of this precipitate is not known since it persisted when the specimens were heat treated above the beta transformation temperature (approximately 1325F) and water quenched.

3. In the 1600 to 2000F temperature range, almost complete re-solution of all of the constituent occurred in the 40-inch and 5-inch diameter blanks (Figures 18 and 19). After the 2000F treatment, both pieces were essentially free of precipitate. In contrast, the plate stock samples had relatively clean structures with some grain boundary precipitate after treatments at 1600F and 1800F, but had matrix and sub-grain boundary precipitation at 2000F (Figure 20).

4. At 2100F, the 40-inch and 5-inch diameter blanks had a coarse grain boundary precipitate (Figures 18 and 19). The plate stock sample has an increased amount of the matrix and subgrain boundary constituent observed after the 2000F treatment.

These results indicated that the precipitate occurring in roll-forgings apparently formed during cooling through the 900 to 1400F temperature range. Grain boundary precipitation at 2100F was discounted because no forging operations were conducted above 2000F. To determine the effect of cooling rate on precipitation, similar samples were heated at temperatures in the range of 1400 to 2000F for two hours and cooled in the center of a 3 1/2-inch diameter, 6-inch long section of titanium bar stock. It was felt that this would simulate the cooling of a forging during fabrication. The resultant microstructures showed that grain boundary and matrix precipitation occurred in all instances where there was slow cooling from the 1400 to 2000F range (Figures 18 and 20). When cooled slowly from 1800F or 2000F, the resultant grain boundary precipitate was coarse with a more spheroidal matrix precipitate. To affirm the previous indication that re-solution could be accomplished by water-quenching from 1800F, a sample of the 40-inch diameter ring was heated at

a temperature of 2000F for two hours, slow-cooled to produce a heavy matrix and grain boundary precipitation, reheated at 1800F for two hours and water-quenched. The resultant structure. shown in Figure 21, was essentially clean.

Samples from the flange sections of the two 40-inch diameter rings were then heat treated and machined into smooth and notched ($K_t = 8$) tensile specimens to determine the relative ductility of the structures discussed above. The heat treatment used was as follows:

1. As-received (roll-forged and solution-treated at 1400F for 30 minutes),

2. 1200F, 1400F and 2000F for two hours and water-quenched, and

3. 1400F, 1800F and 2000F for two hours and furnace cooled.

In addition, except for the treatment at 1200F, smooth tensile specimens were similarly heat treated and aged for 64, 72 and 96 hours at 900F. The results of these tests are shown in Tables XIV and XV, and in Figure 22. This data shows that reheating to 1800F followed by water-quenching produces the best ductility both before and after aging at 900F. In comparison, reheating at 1400F or 2000F followed by water quenching produces lower ductility before and after aging, and reheating at 1200F followed by water quenching produces extremely low ductility. Furnace cooling in all instances produces lower ductility and more sluggish aging response. An illustration of the relative ductilities as indicated by notched ($K_t = 8$) specimen fracture surfaces is shown in Figure 23.

The study indicated a method for improving or restoring the flow-turnability of B-120 VCA titanium roll-forgings containing an unacceptable structure that would otherwise produce surface tears or fracture during the flow-turning operation. Furthermore, the study showed that slow cooling during processing of ring forgings should be avoided.

B. Full Scale 40-Inch Diameter Rings

Seven 40-inch diameter rings were forged at 1900F(furnace soaking temperature)using the technique developed with 14-inch diameter rings. Although the results from forging 14-inch diameter rings indicated that two operations would be sufficient, tooling difficulties encountered during the preliminary operations necessitated a total of four operations to produce the required diameter. The forging sequence used for these pieces is outlined in Table XVI. After rolling, the rings were sized at 1450F and water quenched.

Test pieces were cut from one end of each ring. Typical compositions (in per cent) are:

Ring Number	V	Cr	Al	Fe	O	H	N	C	Ti
2	12.90	10.03	2.89	<0.30	0.13	0.015	0.038	0.05	balance
4	12.90	10.70	2.92	<0.30	0.10	0.021	0.037	0.04	balance

The tensile properties of all seven 40-inch diameter rings were determined in the as-rolled and annealed (1450F (1/2) WQ) condition. The results (shown in Table XVII) demonstrate that all rings had similar properties and that the tensile ductility and notched (K_t = 8) toughness was equivalent or superior to those obtained for 14-inch diameter rings.

Test rings from roll forgings numbers 2, 5, and 7 were annealed for 15 to 30 minutes at 1300, 1450, and 1800F and water quenched. Smooth tensile specimens from these rings were tested and the results (Table XVIII) indicated an increase in tensile elongation and reduction in area with an increase in annealing temperature. Specimens solution treated at 1800F exhibited area reductions of better than 50 per cent. Since previous experience has indicated that reduction in area is a measure of flow-turnability, it was decided to solution treat all of the rings at 1800F before flow-turning, provided it could be shown that the solution treatment did not detrimentally affect the aging response and tensile ductility of the resultant flow-turned cylinders.

To determine the effect of the 1800F solution treatment, two 9.4-inch diameter cylinders, one annealed at 1450F and the other solution treated at 1800F, were flow-turned in two passes with 50 per cent reduction per pass. The cylinders were then evaluated for aging response after stress-relieving for one-half hour at 850F. The results (see Table XIX and Figure 24) showed a rapid and equivalent aging response for both cylinders but erratic and low tensile elongation for the cylinder solution treated at 1800F prior to flow-turning. These results were considered anomolous and therefore a 14-inch diameter ring (number 6) was solution treated at 1800F and flow-turned in two passes. Unfortunately this ring was not properly annealed between flow-turn passes and the test results, which indicated poor tensile properties and unusual aging response, were not considered representative of a cylinder solution treated at 1800F before flow-turning. As a result, four additional 14-inch diameter rings were solution treated at 1800F for 15 minutes, water quenched, and flow-turned by the two-pass technique. The results from testing these cylinders are reported in detail in section V-D, page 37 of this volume and indicate that the 1800F solution treatment does not deleteriously affect the aging response or tensile ductility of the subsequently flow-turned cylinders.

Forty-inch diameter rings numbers 4 and 5 were then solution treated at 1800F for 15 minutes and water quenched. Ring number 4 was flow-turned in two passes and stress relieved at 850F for one-half hour. A test piece was cut from the ring and evaluated for aging response and tensile ductility. The results (discussed in section VII of this volume) were considered satisfactory and the remaining rings were therefore solution treated at 1800F for fifteen minutes and water quenched. Test specimens solution treated with the rings were tested (see Table XX) and again demonstrated that the 1800F solution treatment improved ductility (compare Table XX with Table XVII). The blanks were subsequently flow-turned. Each ring displayed excellent flow-turnability and there were no material failures or intergranular separations on the inside surfaces of the resulting cylinders.

The solution treatment at 1800F for fifteen minutes followed by a water quench has been demonstrated to be an effective method for improved flow-turnability correlating with a dramatic increase in tensile reduction in area of the blank material. The improvement is believed to result from the solution of an undesirable grain boundary constituent formed by slow cooling from temperatures above 1400F.

IV. INITIAL FLOW-TURNING DEVELOPMENT

A. Flow-Turning Parameters

Initially, the flow-turning development program provided typical flow-turned cylinders for the material and heat treatment investigations previously described, and for determining effects of ring rolling and heat treatment factors on flow-turning behavior. In order to evaluate these factors with a minimum of variables, it was decided to use the same flow-turning technique for each blank of the first series. The flow-turning practice that showed the best results during the preceding program (Contract RM-962) was selected for use. This practice utilized the forward flow-turning technique which requires a flanged blank and produces deformation in the direction of roller feed. The blanks were flow-turned in two passes, using approximately 50 per cent reduction in wall section thickness (and simultaneously increasing the blank length by a factor of approximately two) during each pass. The flow-turning was done on a two roller (opposed) 42 by 50 inch Cincinnati Hydrospin machine. The machine parameters were set for 950 or 630 inches per minute mandrel surface speed and a roller feed of 0.015 inch per mandrel revolution per roller. These parameters were established so that a constant working rate could be maintained for each blank regardless of diameter.

The flow-turning starting blank was machined from a roll-forged ring to dimensions commensurate with (1) the required wall thickness, (2) the length of the finished cylinder, (3) the number of passes, and (4) the magnitude of reduction during each pass. The cylinder design for this series required a wall thickness of 0.075 inch. Since two passes were to be used with approximately 50 per cent reduction during each pass, the thickness of the machined blank was established at 0.300 inch. The blank length was not of prime importance during the initial and developmental phases of the program since it was not intended to use the resulting cylinders for rocket motor case parts. All blanks, subscale as well as full scale, were machined to the 0.300-inch wall thickness so that the amount of deformation would be the same for blanks of the various diameters. The machined blank incorporated a chamfer, machined at an angle approximately

equal to the lead angle of the working surface of the roller to the full depth of the reduction to facilitate maximum depth of plastic deformation as soon as plastic deformation commenced. A sketch of a flow-turning starting blank is shown in Figure 25.

The flow-turning rollers used in the initial phases of this program were the same as those previously used to flow-turn B-120 VCA titanium cylinders. These rollers had also been satisfactory for producing steel cylinders. The roller configuration contained a conical lead surface inclined 25 degrees from the blank axis and a flat surface approximately 0.100 inch long at the tip. (See Figure 26)

B. Flow-Turning of Subscale and Full Scale Cylinders

Two 9.4-inch and two 40-inch diameter roll-forged rings, available from a previous program, were flow-turned by the initial practice to provide cylinders for evaluation. These cylinders were used for the material and heat treatment investigations previously described. In addition, the 40-inch diameter cylinders were used for sizing experiments. It is interesting to note the problems which occurred during the processing of these cylinders since they were indicative of the areas requiring further development.

The two 9.4-inch diameter roll-forged rings were flow-turned in two passes (approximately 50 per cent reduction per pass) to a wall thickness of about 0.075 inch. The dimensions of the cylinders and the parameters employed are tabulated in Table XXI. Between flow-turn passes the cylinders were stress-relieved at 850F for 30 minutes and a section trimmed from each for determination of an intermediate annealing treatment.

Annealing at 1500F for 15 minutes produced the optimum condition with complete recrystallization and limited grain growth through the wall thickness. The parts were given this treatment. After annealing, the cylinders were pickled in an aqueous solution of 3.5 per cent HF (70 per cent concentrate), and 35 per cent HNO_3 to remove 0.002 inch per surface of contaminated (oxygen rich) material. Because of the radial growth during the first pass, both cylinders were shrunk by a

sizing operation to mandrel size for the second pass. Both cylinders again grew radially and also bulged locally during the second pass. Dimensions were not taken after this pass because the cylinders were immediately sectioned in the as-flow-turned condition for determination of residual stresses and the optimum stress-relief treatment.

The two 40-inch diameter roll-forged rings (numbers 7 and 8 in Table XXI) were given the first flow-turn pass after being annealed at 1450F for 30 minutes. The cylinders were then stress-relieved at 850F for 30 minutes and an intermediate annealing treatment was determined. Microexamination of annealed test samples showed that the optimum treatment was heating at 1550F for 15 minutes. After annealing, the cylinders were pickled in an aquaeous 3.5 per cent HF (70 per cent concentrate), 35 per cent HNO_3 solution to remove 0.004 inch per side of contaminated (oxygen-rich) skin. Both cylinders grew radially approximately 0.250 inch on the diameter during the first flow-turn pass and cylinder number 8 bulged locally in addition to growing radially. Visual and fluorescent penetrant inspection of cylinder number 8 before and after pickling revealed several cracks on the outside surface in the locally bulged area. These cracks were removed by blending prior to pickling but reappeared after pickling. Additional blending to a depth of 0.050 inch was required to remove the defects. The depth of these blended regions was considered too great for subsequent flow-turning so the locally bulged area was trimmed off.

Cylinder number 7 ruptured during shrinking to mandrel size in preparation for the second flow-turn pass (Figures 27 and 28). The cylinder had been shrunk approximately 0.210 inch on the diameter when failure occurred. No defect was apparent to account for failure. Cylinder number 8 was then instrumented with strain gages to evaluate the stress conditions during shrinking. During shrinking, the strain gages were continually monitored to determine if local highly stressed regions appeared around the cylinder circumference. The gages indicated no abnormal stress distributions and gave essentially equivalent strains around the circumference after yielding had occurred. As an additional precaution, it was decided to stress-relieve the cylinder after shrinking approximately half the desired amount on the diameter (0.125 inch). The cylinder was therefore re-annealed at 1400F for 15 minutes and shrunk the remaining 0.125 inch on the diameter to mandrel size. The cylinder was

then given the second flow-turning pass to a wall thickness of about 0.080 inch as outlined in Table XXI. Radial growth but no local bulging occurred during the second pass. The cylinder was cut axially to provide material for the various investigations. The sectioning was done in the as-flow-turned condition so that the cylinder would open circumferentially to provide flat material for tensile specimens. The cylinder was also instrumented with strain gages to determine the residual stress level in the as-flow-turned condition.

C. Problems Requiring Further Development

The cylinders described in the previous section were flow-turned using the roller configuration and practice developed during a prior contract (RM-962). This flow-turning practice and roller configuration produced radial growth and local bulging on the cylinders which was similar to that experienced during previous work. The radial growth relative to flow-turning parameters (roller feed and per cent reduction) is shown in Table XXI and Figure 29. Radial growth is expressed as the diametral change per inch of diameter and the flow-turning feed-reduction parameter is expressed as a product of effective roller feed (feed in inches per mandrel revolution per roller) and per cent reduction. The diametral growth expressed as growth per inch of cylinder diameter should be applicable to all cylinders regardless of diameter. The flow-turning parameter expressed as a product of feed and reduction is used since flow-turning performance is most responsive to changes in these variables.

The results of testing the series of cylinders discussed in this section has shown that excessive radial growth (as much as 0.026 inch/inch of diameter) and local bulging occurred as a result of the flow-turning practice utilized. The shrinking experienced with two 40-inch diameter cylinders indicated that 0.125-inch diametral shrinking could be accomplished after the first pass providing the material was properly annealed. Diametral shrinking greater than 0.125 inch, although successfully achieved without re-annealing in the previous program, in some instances resulted in buckling failures during the shrinking operation. This experience

indicated that the development program should be directed toward improving the flow-turning practice whereby the diametral growth of full scale cylinders would be reduced to 0.100 inch or less (0.0025 inch per inch of diameter), and all associated local bulging eliminated. On the basis of the tensile findings, it was decided to study the flow-turning process in order to determine and control operational variables to attain structural quality and close dimensional tolerance.

V. SUBSCALE FLOW-TURNING DEVELOPMENT

A. Background

Major problems encountered during previous experience in the flow-turning of B-120 VCA cylinders were radial growth and local bulging which were unpredictable and of considerable magnitude. Although the cylinders produced by early flow-turning methods had adequate strength properties, dimensional control was not acceptable for production of rocket motor cases and the amount of shrinking required to offset radial growth was intolerable. The objective of this development program was to define operating parameters and to develop a revised flow-turning practice which would reduce radial growth, (not to exceed 0.0025 inch per inch of diameter), and to eliminate local bulging.

Since the experience with the initial flow-turning practice (described in the previous section) indicated that similar problems were encountered with cylinders ranging in diameter from 9.4 to 40 inches, it was reasoned that a revised flow-turning practice could be developed with subscale cylinders and applied successfully to full scale 40-inch diameter cylinders.

An analysis was made of all previous experience in the flow-turning of titanium at Pratt & Whitney Aircraft, and the parameters expected to affect radial growth and bulging were evaluated. This analysis indicated that the largest gains would be obtained by changes in the roller geometry. A conical roller configuration which was satisfactory for flow-turning steel cylinders had been used for most of the early B-120 VCA titanium flow-turning. No combination of available machine settings showed promise of providing dimensional stability with titanium cylinders using this roller configuration. A limited amount of experimentation had been done with a sharp parabolic roller contour which produced less radial growth than other roller contours on titanium cylinders.

B. Evaluation of a Revised Roller Configuration

Based on preliminary indications that roller geometry would have a marked influence on flow-turning results with B-120 VCA

titanium, a series of experiments were prepared to evaluate the original parabolic roller. Both 9.4-inch diameter and 14-inch diameter starting blanks were prepared by rolling and longitudinally welding 0.375-inch thick plate stock. Flanges were welded to one end of the rolled and welded plate stock and the assembly was machined into flow-turn blanks with approximately 0.300-inch wall thicknesses. (It was not the intent of this experiment to develop rolled and welded blanks for this application. This method of fabrication was used only for expediency to obtain basic flow-turning information prior to flow-turning development using roll-forged starting blanks.)

The initial program included evaluation of a series of eight 9.4-inch diameter cylinders flow-turned on a single-roller 60 by 74-inch Lodge & Shipley machine. The purpose of this series was to compare two-pass and three-pass methods and to evaluate the effect of variations in per cent reduction, mandrel speed, feed rate, and roller tilt angle on the radial growth and local bulging of cylinders flow-turned with a parabolic roller. The roller was 14 inches in diameter and had a parabolic lead contour with a tip radius of 0.062 inch (See Figure 26). Lubriplate 630AA was used as a lubricant between the blank and mandrel and a low viscosity sulfurized fatty mineral oil was sprayed ahead of the roller as a coolant.

The flow-turning parameters and resulting cylinder dimensions for this series of tests are shown in Table XXII. The first two blanks were flow-turned in the as-welded condition. The first of these blanks, which was flow-turned at 25 per cent reduction commensurate with a three-pass sequence, failed immediately after the start of flow-turning. The failure originated in the circumferential flange weld in an area of incomplete weld penetration. The second blank was flow-turned for approximately 25 per cent of its length with a 38 per cent reduction when flow-turning was intentionally terminated. When flow-turning was resumed, failure occurred at the point of termination. The fracture propagated circumferentially along the roller path.

Blanks numbers 3 and 4 were flow-turned successfully with first pass reductions of 44 and 42 per cent and second pass reductions of 63 and 54 per cent, respectively. Blank number 3 was annealed at 1825F for 30 minutes after welding and prior to flow-turning while blank number 4 was flow-turned in the as-welded condition to determine if heat treating of the welds was necessary prior to flow-turning these rolled and welded blanks.

Both cylinders were annealed and completely recrystallized at 1600F for 30 minutes in an argon atmosphere and vapor blast-cleaned prior to the second flow-turn pass. Cylinder number 3, which had been annealed prior to flow-turning, was free of defects on the inside surface of the axial weld, whereas cylinder number 4 which had not been annealed after welding contained small surface tears in the weld. As a result of these tests, all subsequent blanks fabricated from rolled and welded plate stock were annealed prior to flow-turning. Figure 30 shows typical blanks in the as-welded, machined, and flow-turned conditions after the first and second passes.

Blank number 5 was given the first flow-turn pass with a reduction of 25 per cent, commensurate with a three-pass sequence, to repeat evaluation of a three-pass method since the results of flow-turning blank number 1 were not considered valid. This blank cracked severely on the inside surface after flow-turning approximately three inches of its length. The cracking was indicative of insufficient plastic deformation on the inside surface which was considered to be the result of the relatively light reduction of 25 per cent during the first pass. The reductions intended for the three-pass method were 25, 33.3 and 50 per cent respectively. These reductions were established to provide approximately 50 per cent reduction during the last pass to assure maximum cold working through the section thickness. It is very important that ample and uniform cold working throughout the section thickness be accomplished during the last pass with B-120 VCA titanium cylinders in order to achieve the desired aged properties. As a result, the first two passes were required to have relatively low reductions with the starting blank thickness chosen. Since small reductions may fail to produce plastic deformation through the section thickness (as was the case with blank number 5), the three-pass method would apparently require a greater starting blank thickness to allow larger reductions on the first two passes. On this basis, the two-pass method was favored since the same objective could be achieved with a fewer number of operations. The two-pass method with approximately 50 per cent reduction per pass was therefore adopted for all the subsequent flow-turning conducted for this program.

Cylinder number 6 was flow-turned in two passes with the roller tilted in the direction of feed by the amount of helix angle generated by the roller circumferential path. Strain gage analysis of this cylinder suggested a lower residual stress in the

as-flow-turned condition but the results are considered inconclusive because of the unknown effect on residual stress imposed by the axial weld in the cylinder wall. No improvement in radial growth was observed to result from the roller tilt so further study of this parameter was dropped for this flow-turning program.

Cylinders numbers 7 and 8 were flow-turned in two passes with increased roller feed. This resulted in reduced diametral growth during both passes, with negative growth occurring in both cylinders during the second pass, indicating that significant reduction in diametral growth was possible using the new parabolic roller configuration during both the first and second passes. Figure 31 shows effects of varying the flow-turning feed-reduction parameter on the diametral growth of the 9.4-inch diameter cylinders. With proper selection of this parameter it should be possible to prevent radial growth. It can be seen that a curve drawn through an average of the data passes through zero unit growth at a feed-reduction parameter of 0.010. Therefore at a reduction of 50 per cent, a feed of 0.020 inch per mandrel revolution per roller should be the optimum value for preventing radial growth and no local bulging should occur.

The cylinders in this series of tests were free from local bulging after the first pass and the diametral growth was less than that experienced during previous work. Metal tearing occurred on the inside surface of the axial weld in most blanks during the first pass. These were generally shallow surface tears within the length of the flow-turned portion and one or two deep tears at the beginning and end of the flow-turned section. These tears did not extend into parent material and did not propagate during subsequent flow-turning. Because of the presence of these tears, the blanks were not sized to correct the loose fit of the blanks on the mandrel prior to the second pass. The second flow-turn pass at the higher feeds and reductions produced little or no radial growth. However, because of the loose fit of the blank, local bulging occurred on some blanks. The higher feeds, however, were also effective in reducing the amount of bulging. Figure 32 shows the inside surface of a typical 9.4-inch diameter flow-turned cylinder from this series of experiments.

The next phase of the flow-turning program was to evaluate (1) the effect of scaling from 9.4-inch to 14-inch diameter cylinders, (2) the effect of changing from a single roller to a two-roller flow-turning machine and (3) to determine whether the feed-

reduction parameter optimized in the previous series of tests would hold constant with the same roller configuration.

The change from a single-roller to a two-roller machine was a necessary step toward flow-turning full scale parts. The roll forces necessary to flow-turn B-120 VCA titanium alloy produce severe mandrel deflection on the single roller machine to the extent that a negative roller-mandrel gap setting is necessary to produce a 50 per cent reduction during the second pass. This objectionable machine deflection can be reduced by using a hydrospin machine with two opposing rollers. Reduced mandrel deflection allows better control of reduction and wall thickness. In transferring the flow-turning from the one-roller to the two-roller machine, the optimized roller feed of 0.020-inch per mandrel revolution per roller was applied to both rollers, thereby doubling the carriage feed in inches per minute. The remaining 9.4- and 14-inch diameter blanks fabricated from rolled and welded plate stock failed in the circumferential flange weld when flow-turning was attempted on the two-roller machine. Failure was attributed to the increased axial flow-turn load imposed by the two-roller action. Since the use of rolled and welded blanks was only for expediency, there was no further attempt to develop this type of blank.

C. Development with 14-inch Diameter Roll-Forged Rings

The next series of experiments were conducted on ten 14-inch diameter roll forged rings. The intent of these experiments was to evaluate the effect of scaling-up in diameter, to evaluate the performance of the parabolic contoured roller with a two-roller machine, and to optimize flow-turning parameters in preparation for fabricating 40-inch diameter full scale cylinders.

The ten 14-inch diameter roll-forged rings were solution treated at 1450F for 30 minutes, water quenched, and machined into flow-turn blanks. Six of these rings were flow-turned utilizing the optimum technique as determined by previous experiments, including the parabolic roller configuration. All of the flow-turning was accomplished on a two-roller 42 by 50-inch Cincinnati Hydrospin machine. The flow-turning parameters and cylinder dimensions are listed in Table XXIII.

The first blank was flow-turned close to the previously determined optimum feed-reduction parameter of 0.010, using a feed of 0.020 inch per mandrel revolution per roller and

as-flow-turned condition but the results are considered inconclusive because of the unknown effect on residual stress imposed by the axial weld in the cylinder wall. No improvement in radial growth was observed to result from the roller tilt so further study of this parameter was dropped for this flow-turning program.

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The cylinders in this series of tests were free from local bulging after the first pass and the diametral growth was less than that experienced during previous work. Metal tearing occurred on the inside surface of the axial weld in most blanks during the first pass. These were generally shallow surface tears within the length of the flow-turned portion and one or two deep tears at the beginning and end of the flow-turned section. These tears did not extend into parent material and did not propagate during subsequent flow-turning. Because of the presence of these tears, the blanks were not sized to correct the loose fit of the blanks on the mandrel prior to the second pass. The second flow-turn pass at the higher feeds and reductions produced little or no radial growth. However, because of the loose fit of the blank, local bulging occurred on some blanks. The higher feeds, however, were also effective in reducing the amount of bulging. Figure 32 shows the inside surface of a typical 9.4-inch diameter flow-turned cylinder from this series of experiments.

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The first blank was flow-turned close to the previously determined optimum feed-reduction parameter of 0.010, using a feed of 0.020 inch per mandrel revolution per roller and

reductions of 51.8 per cent and 49.5 per cent on the first and second passes. This cylinder exhibited good dimensional stability on both passes which showed good correlation with previous results and indicated that the feed-reduction parameter was valid with increasing diameter and a change from one to two rollers. However, metal tearing occurred on the inside surface during the first pass, mostly within one inch of each end of the flow-turned section, as shown in Figures 33 and 34.

Forged rings numbers 2 through 5 were flow-turned with changes in the various flow-turning parameters to determine which parameter was most effective in reducing inside surface tearing during the first pass. The changes in parameters during the first pass were, 1) increased roller tip radius, 2) less reduction, and 3) reduced roller-feed rate. These changes were applied singly and evaluated on the basis of incidence of inside surface tearing. The results of this experiment showed that reduced roller-feed rate was most effective in reducing surface tearing although the surface tearing was not completely eliminated.

It appeared that the flow-turning practice was not the basic cause of the surface condition and thus attention was diverted to the starting material. The forged rings had been solution treated at 1450F. Early studies of ring-forging annealing practices had shown improved ductility after solution treatment at 1800F and a water quench. This latter treatment was not used for the forged rings, however, since tests conducted on 9.4-inch rolled and welded cylinders had indicated poor aged ductility after 1825F solution treatment and subsequent flow-turning. As described in section III-B, test specimens from full scale rings were solution treated at 1300, 1450, and 1800F for from 15 to 30 minutes and results from testing these specimens (Table XVIII) indicated that greater tensile elongations and reductions in area result from higher solution treatment temperatures. Additional tensile properties were then determined for full scale test ring material which had been solution treated at 1450F and subsequently re-solution treated at 1800F for various times. The results (Table XXIV) again demonstrated the excellent ductility attained with an 1800F-solution treatment and indicated that maximum ductility with minimum grain coarsening was achieved after 15 minutes of treatment.

On the basis of the annealing treatment evaluation, 14-inch diameter ring number 6 was given an additional annealing treatment at 1800F for 15 minutes followed by a water quench, and was flow-turned during the first pass with a reduced roller-feed rate similar to that used with ring number 5. Visual and nondestructive inspection showed cylinder number 6 to be free from surface tears after the first pass. The improved ductility of the starting blank from the 1800F annealing treatment was apparently required to eliminate surface metal tearing with the feed rate used to minimize diametral growth.

The effect of the changes in flow-turning parameters on diametral growth with cylinders 1 through 6 is shown in Figure 35. The tearing condition during the first pass did not affect the flow-turning response to these changes, and all cylinders were given the second flow-turning pass to evaluate changes. With a roller tip radius of 0.062-inch (the same as that used for 9.4-inch diameter cylinder experiments), a feed-reduction parameter of about 0.010 still appeared to be optimum for eliminating diametral growth during both flow-turning passes. Rollers with larger tip radii of 0.100 and 0.220 inch had been fabricated to evaluate methods for eliminating the severe thread pattern produced by the sharp 0.062-inch tip radius. These rollers had the same parabolic lead contour (see Figure 26) blended with a larger radius to produce a blunt tip. The rollers with a tip radius of 0.100-inch were used for the first pass of cylinder number 2 in an effort to eliminate surface tearing. This did not correct the problem and the diametral growth increased considerably. The rollers with larger tip radii were used in all other cases during the second pass for the purpose of improving the prior surface finish. These rollers did produce an improvement, although they did not completely eliminate the thread pattern. The diametral growth, however, increased with an increase in roller tip radius, giving a unit growth above 0.003 inch per inch of diameter at a feed-reduction parameter close to 0.010 with a roller tip radius of 0.220 inch. Local bulging of the cylinders was found to be a direct result of an increase in blank diameter from mandrel size as a result of diametral growth. In the absence of diametral growth, local bulging did not occur. Based on the objectional growth trend, further evaluation with the 0.100 and 0.220 inch tip radii rollers was discontinued.

Tensile tests on specimens from cylinder number 6 following the second pass and a stress-relieving treatment showed low ductility due to an inside surface condition (yielding and intergranular separations) throughout the flow-turned area. Microexamination of material from the flow-turned ring showed that incomplete recrystallization had existed adjacent to the inside surface prior to the second pass and grain boundary precipitate was abundant throughout, with evidence that the precipitate existed prior to the second pass. It was apparent that cylinder number 6 had not received a satisfactory annealing treatment between flow-turn passes. An improved annealing practice was developed on subsequent cylinders.

Numerous pits were found on the inside surface of cylinder number 6, and to various degrees on cylinders 1 through 5. These pits were considered to be caused by metal being transferred from the blank to the mandrel, Figure 36. To prevent metal transfer, all subsequent cylinders were coated with a colloidal graphite suspension (Fel Pro C-200). Pitting was significantly reduced and in most cases eliminated.

Ring number 7 was annealed at 1800F for 15 minutes followed by a water quench prior to flow-turning. The first flow-turn pass was performed with a reduced roller feed rate similar to that used for cylinder number 6. The inside surface was coated with a colloidal graphite suspension to prevent the transfer of material from the inside surface of the blank to the mandrel. Visual and nondestructive inspection showed this ring to be free of tears on the inside surface after the first pass. Between the first and second passes the microstructure of a section of the ring was examined after various annealing treatments, and 1500F for 30 minutes followed by air cooling was established as the optimum annealing practice prior to the second pass. After the first flow-turn pass, an area was blended to a depth of 0.025 inch to simulate removal of a surface defect that might occur during the first pass operation. Cylinder number 7 was then given the second flow-turning operation, (see Figures 37 and 38). The depression was completely filled and no cracking or unusual behavior was noted. This cylinder was used to evaluate the effects of the 1800F anneal on the aging response characteristics.

Ring number 8 was also annealed at 1800F for 15 minutes and water quenched. The first flow-turn pass was performed with an increased roller feed rate necessary to obtain the desired feed-reduction parameter and to determine whether the modified annealing cycle would prevent surface tears at this condition. The inside surface was coated with colloidal graphite as before. Visual and nondestructive inspection of the inside surface of the ring after the first pass showed no tears. However, there were some cracks on the outer surface of the ring at the start of the flow-turned area. These cracks were attributed to a machine malfunction at the beginning of the flow-turning cycle and were not found to be detrimental through the remainder of flow-turning operations on this ring. The modified intermediate annealing cycle developed for cylinder number 7 was applied to cylinder number 8. No difficulty was encountered during the second flow-turn passes.

A roller tip radius of 0.062 inch was used in flow-turning cylinders 7 and 8 and there was essentially no diametral growth of either. Each second pass included contour flow-turning to provide a heavier section for the weld joints as shown in Figure 25. Cylinder number 8 demonstrated that the material condition was now optimum and that flow-turning could be accomplished with parameters that produced very little or no radial growth and no local bulging.

Subsequent evaluation of the tensile properties of cylinders numbers 7 and 8 (discussed in section V-D) showed erratic properties which were believed to be a result of roller misalignment during flow-turning. It was found that the Hydrospin machine was not capable of keeping the two opposed rollers opposite one another under the loads required to flow-turn B-120 VCA titanium. Analysis of the machine behavior indicated that one roller was axially displaced from the other in excess of 0.125 inch under extreme operating conditions. Although roller misalignment does not ordinarily have adverse effects on most steels, it is detrimental to the aged properties of B-120 VCA titanium alloy. The optimum practice established under this program requires an effective feed rate of 0.020 inch per revolution per roller. An alignment error of 0.010 inch or greater would cause the lagging roller to deform material that had been cold-worked by the leading roller. In addition, the lead roller would carry the entire working load, resulting in the flow-turning operation being performed at double the effective feed rate. The combined effects could cause microcracks on the outside surface as were noted in cylinders numbers 7 and 8. It is this condition that was considered to be the cause of erratic tensile behavior in the axial direction with these cylinders.

A study was made to determine the revisions necessary to the Hydrospin machine to provide better roller alignment and thus a more accurate control of effective roller feed. To analyze the machine behavior during the flow-turning operation, pressure gages were installed in the hydraulic loading systems on both roller carriages. These gages indicated that the master carriage would consistently assume the major portion of the flow-turning load although the rollers were accurately aligned under no-load conditions. A dial indicator was mounted on a support extending between both roller carriages and bridging the mandrel to measure roller misalignment under load conditions (see Figure 39). The dial indicator showed that the slave roller would lag behind the master roller under feed loads. The amount of misalignment would vary with feed load with a maximum of a 0.200-inch misalignment recorded under maximum feed loads. Using the bridged indicator to measure the relative position of the rollers, it was possible for the operator to advance the slave roller into alignment with the master roller during the flow-turning operation through the use of the machine controls provided. This method was found particularly helpful in maintaining roller alignment during contour flow-turning of reinforced sections for weld joints when feed loads were changing. The effectiveness of this roller aligning method was indicated by the pressure gages which showed approximately equal hydraulic loading of the carriages.

The last two subscale forged rings, numbers 9 and 10, were flow-turned to determine the effects of improved roller alignment and a modified roller configuration. These rings were given the initial solution treatment and between-pass annealing treatment established with the previous cylinders in this test series. Both cylinders were flow-turned with a slightly high feed-reduction parameter of 0.011 due to reductions of 55.2 and 53.5 per cent respectively. A modified roller configuration was designed to improve final surface finish. The pronounced feed lines produced by the previously used rollers with a sharp tip radius of 0.062 inch had not caused any apparent reduction in axial tensile strength, but improved surface finish was desired for full scale parts. Since rollers with increased tip radius had caused too much diametral growth, new rollers were prepared consisting of the same parabolic configuration but with a modified tip as shown in Figure 26.

Blank number 9 was given the first flow-turn pass with the modified rollers and the original sharp 0.062-inch tip radius rollers were used for the first pass with blank number 10. The results showed that the modified rollers significantly improved the surface finish without affecting dimensional control. It was expected that the modified rollers might give some increase in diametral growth, but the data showed the opposite trend. The unexpectedly high growth with cylinder number 10 was attributed to roller misalignment. During the first pass of cylinders 9 and 10, an attempt was made to solve the roller misalignment problem by reducing roller carriage feed. This was done because it was believed that the carriage hydraulic system flow capacity was marginal at the previously used 4 inches per minute per roller carriage feed. Since the marginal hydraulic flow capacity was believed to contribute to roller misalignment, a lower feed rate of 3 inches per minute per roller was used during the first pass with the mandrel speed reduced to 150 to maintain the 0.020 inch per revolution per roller effective feed. A mandrel speed of 200 had been used previously on cylinders 1 through 8. The results of the experiment showed that roller misalignment was not correctable by reducing the feed rate, but it did indicate that changes in mandrel speed did not measurably affect flow-turning performance in the range evaluated.

During the second flow-turning pass of cylinders 9 and 10, proper alignment of the rollers was maintained by the use of the bridged indicator on the Hydrospin machine. As a result of the satisfactory performance on these two blanks, the bridged indicator was used to maintain roller alignment on all subsequent flow-turning operations. The modified rollers were used for the second pass and the cylinders were flow-turned to a wall thickness approximating that required for the full scale design. Contoured weld joints were included. A mandrel speed of 150 and a feed rate of 3 inches per minute per roller were used. Cylinder number 9 has essentially no diametral growth with a reduction of 48.2 per cent during the second pass. Cylinder number 10 had the expected amount of growth associated with a feed-reduction parameter of 0.0085 which resulted from the lower reduction of 42.5 per cent on this cylinder. (See Table XXIII and Figure 35 for flow-turning parameters and growth results compared with the other cylinders in this series).

Concurrent with development of flow turning and heat treatment practice using subscale cylinders, methods for contamination removal and sizing between flow-turn passes were established. Pickling in an aqueous solution of 3.5 per cent HF (70 per cent concentrate) and 35 per cent HNO_3 to remove 0.002 to 0.004 inch of surface contaminated (oxygen-rich) material was used after annealing and before sizing (if required), or flow-turning. Sizing was accomplished by shrinking when diametral growth exceeded approximately 0.001 inch per inch of diameter, or by expanding to allow the cylinder to be positioned on the mandrel without an interference fit when negative growth was experienced. The radial clearance between the 14-inch diameter cylinders and the mandrel was controlled to within 0.0015 and 0.003 inch. It was found that an excessively loose blank-to-mandrel fit caused circumferential distortions and possibly variations in wall thicknesses. Variations in the final cylinder wall thickness also resulted from variations in the wall thickness of the starting blank which were carried through the flow-turning operations.

In summary, the flow-turning program with subscale 14-inch diameter roll-forged rings was successful in arriving at a practice that would produce cylinders with little or no diametral growth and with no local bulging. Mechanical properties of cylinders produced by this practice were found to be excellent. Metal tearing on the inside surface of the cylinders during the first pass was eliminated by obtaining adequate ductility in the starting blank through revised solution treatment. Improved surface finish was obtained (without affecting diametral growth) through the use of a modified tip design for the parabolic rollers. A revised operating procedure with the two-roller Hydrospin machine improved roller alignment, thereby distributing the work evenly between the two rollers which eliminated external surface cracking and improved mechanical properties of the flow-turned cylinders. Experiments indicated that the feed-reduction parameter (inches of feed per mandrel revolution per roller multiplied by reduction) directly affected radial growth. Local bulging was found to be the result of an increase in starting blank diameter from mandrel size as a result of diametral growth. It was further demonstrated that, in the absence of radial growth, local bulging would not occur.

The optimum feed and reduction to eliminate radial growth with the final parabolic roller design was found to be 0.020 inch per revolution per roller with 50 per cent reduction. Minor variations in each factor were permissible providing the feed-reduction parameter remained 0.010. The close agreement in unit growth results between these 14-inch diameter cylinders and the previous test program with 9.4-inch cylinders gave assurance that the flow-turning parameters developed could be successfully applied to full scale 40-inch diameter cylinders.

D. Evaluation of Subscale Cylinders

Residual Stresses in Flow-Turned Cylinders - It would be expected that high residual stresses would result from the large deformations which occur in the flow-turning operations. To determine the amount of residual stress present in flow-turned cylinders in the as-flow-turned condition after the final pass, a hoop five inches wide was cut from a 9.4-inch diameter cylinder, instrumented with strain gages, and cut axially. The hoop showed an average circumferential tension stress of 150,200 psi and an axial tension component of 144,800 psi. When cut axially, it opened to form an essentially flat section with a small helical twist. Representative sections of this cylinder intact and cut axially in the as-flow-turned condition are shown in Figure 40.

To evaluate the residual stress gradient through the wall thickness, two one-half inch wide 9.4-inch diameter hoops were cut from one cylinder in the as-flow-turned condition. Narrow sections were used to minimize the axial component of the residual stress. To determine the residual stresses through the outside half of the wall thickness, one hoop was instrumented with strain gages on the inside surface and then pickled to remove material from the outside surface. Alternatively, to determine the residual stresses through the inside half of the wall thickness, the other hoop was pickled to remove material from the inside surface with the strain gages mounted on the outside surface. The calculated stress levels at intervals through the wall thickness are shown in Figure 41. The results showed the outside half of the wall thickness to be in tension with a maximum circumferential stress of approximately 200,000 psi occurring at a depth of 0.012 inch. The inside half of the thickness was in compression with a maximum stress of about 110,000 psi, also at a depth of approximately 0.012 inch.

Two other cylinders, with diameters of 14 inches and 40 inches, were sectioned longitudinally in the as-flow-turned condition and the residual stresses were determined. Test results from the 14-inch diameter cylinder indicated residual tension stresses of 188,200 psi in the axial direction and 146,200 psi in the circumferential direction. Results from the 40-inch diameter cylinder indicated residual tension stresses of 174,000 psi circumferentially. The variation in magnitude of these stresses is believed to be associated with variations in flow-turning parameters during the final pass.

The need for stress-relieving B-120 VCA titanium flow-turned cylinders before sizing and welding to other components was apparent from these tests.

Stress Relief of Flow-Turned Cylinders - Prior to welding a B-120 VCA flow-turned cylinder to the other components of a rocket motor case, the cylinder must be sized to the required diameter and must be aged to the required strength level. Since the cylinder should possess adequate ductility for sizing, the recommended sequence of operations following flow-turning is to stress-relieve, size, and then age the cylinder.

Thus, the optimum stress-relief heat treatment should provide the best combination of the following:

1. Relief of a minimum of 50 per cent of the residual stresses after flow-turning,

2. Adequate ductility after stress-relief for subsequent sizing operations, and

3. Rapid maximum aging response after stress-relief and high toughness in the fully aged condition.

Initial tests were run to determine the stress-relieving heat treatment which would provide maximum ductility. Smooth tensile specimens were machined in the circumferential direction from cylinders in the as-flow-turned condition and were heat treated for various times at temperatures from 600 to 950F. Data from testing these specimens (Table XXV and Figure 42) showed that increased ductility and decreased yield strength as compared to the as-flow-turned condition could be achieved by

heat treating for an appropriate time at each temperature in the 600 to 950F range. The time at temperature to achieve the minimum yield strength and maximum elongation decreased with increasing heat treatment temperature. Most significantly, the highest values of elongation and lowest values of yield strength occurred with the highest stress-relieving temperatures.

Another series of tests were conducted to determine the speed of aging response following stress-relief. Tensile specimens which had been given the stress-relieving treatments described above were aged for various times at temperatures between 700 and 900F. Test data from these specimens indicated that the speed of aging response increased with decreasing stress-relieving temperature and with decreasing time, as shown in Table XXVI and in Figures 43 and 44.

To determine the stress-relief and aging combination producing optimum notched toughness, both smooth and notched ($K_t = 8$) tensile specimens were machined from a 14-inch diameter flow-turned cylinder and tested after aging to the 190,000 psi yield strength level. The resultant data indicated a trend toward decreased notch sensitivity with decreasing stress-relief and decreasing aging temperatures (Table XXVII).

The reduction in residual stress was evaluated after stress-relief treatment and after subsequent aging of flow-turned material since both parts of the duplex heat treatment were expected to reduce residual stresses. Circumferential sections 1 inch by 3 inches were cut from 9.4-and 40-inch diameter cylinders in the as-flow-turned condition. These sections were stressed by bending in a stainless steel fixture to 65,000 psi, and then heat treated. Strain gages were attached to the piece, zero readings taken, and then the fixture was removed and final strain gage readings taken. The residual stress was calculated from the difference between strain gage readings. Specimens were (1) directly aged at 800F, (2) stress relieved at 850F for 30 minutes, and (3) aged at temperatures between 700 and 800F after an 850F stress-relief treatment. The results of these tests are shown in Tables XXVIII and XXIX and in Figure 45. The results are expressed in terms of per cent stress relief since this parameter has been found to be insensitive to the initial residual stress. As anticipated, the degree of relief increased with both increasing stress-relief time

and temperature in the 600 to 950 range. Treatments below 800F did not appear feasible since only 50-per cent relief was achieved after 8 hours at 700F. Based on using the lower temperatures (less than 900F) for optimum aging behavior (high strength with maximum ductility and toughness) while obtaining adequate residual stress reduction, stress-relief at 850F followed by aging at 800 to 900F appeared to be the most satisfactory compromise.

Smooth tensile specimens were also machined from these cylinders after annealing at 1400 to 1500F and aging at 800 to 900F. Annealing after the second flow-turn pass would produce the optinum condition for sizing, minimum yield strength, and maxiimum ductility, as well as complete stress-relief. Specimens were annealed at 1400F for 30 minutes, 1450F for 15 minutes, or 1500F for 5 minutes and then aged at 800F or 900F. The resultant tensile properties (70F) are tabulated in Table XXX and aging curves shown in Figures 46 through 48. The data showed similar aging response after the three annealing treatments with more rapid response at 900F than at 800F. The elongation at the 180,000 psi yield strength level was satisfactory (about 8 per cent) despite the long aging time required (72 hours). This technique was not considered further since dimensional control during flow-turning was sufficiently refined that extensive sizing became unnecessary. The aging times were excessive and it was doubted that high strength levels (200,000 psi yield strength) could be obtained.

Aging Response - Eight 14-inch diameter rings were flow-turned and evaluated for aging response. The first four of these were evaluated to determine the effects of variations in forging practice on the aging response of the subsequently flow-turned cylinders, and the remaining four were evaluated to determine the effects of variations in flow-turning on aging response.

Three of the first four rings were rolled in single operations at 2000, 1900, and 1800F respectively. The fourth ring was rolled in three operations at 2000, 1900, and 1800F. All of the rings were annealed at 1450F for one-half hour and water quenched. They were then flow-turned by a two-pass technique with about 50 per cent reduction per pass. Aging responses were determined after the cylinders were stress-relieved at 850 to 900F or annealed at 1400F. In addition, the first three cylinders were evaluated for tensile property uniformity. The results from these series

of tests appear in Tables VIII and XXXI through XXXVI and in Figures 49 through 55. Evaluation of this data has indicated the following:

1. Cylinders numbers 1, 2, and 3 exhibited similar aging response at 700 to 900F after stress relieving at 900F for one hour (Figures 49, 50, and 51) and after annealing for one-half hour at 1400F (Figure 52). The apparently faster aging response of cylinder number 3 following stress relief may be discounted when the tensile properties presented in Table XXXII are considered. These data demonstrate that the aging response of cylinders flow-turned in two passes with an interim annealing treatment is independent of the rolling technique within the temperature range of 2000 to 1800F.

2. Excellent ductility (about 6 per cent elongation) was obtained with cylinders numbers 1, 2, and 3 by stress relieving at 900F for one hour and aging to the 180,000 psi yield strength level in the axial direction.

3. A high degree of notched (K_t = 8) and smooth tensile property uniformity was exhibited by cylinders 1, 2, and 3 after stress relieving and aging to the 180,000 psi yield strength level. The tensile strength in the circumferential direction was about 10,000 psi greater than in the axial direction and the notched strengths in the two directions were about equal.

4. The 900F aging response for cylinders numbers 1, 2, and 3 after annealing at 1400F for one-half hour and water quenching was very sluggish with 96 hours being required to attain a yield strength between 174,000 and 187,000 psi. This processing sequence was considered impractical and was not further investigated.

5. The aging response of cylinder number 4 after stress relieving at 900F for one hour was only slightly more rapid than for cylinders numbers 1, 2, and 3. This provides further evidence that aging response is not affected by rolling technique within the range of techniques investigated. It is noted that the slightly faster aging response of cylinder number 4 is a result of the greater reduction received during the second flow-turn pass. This is substantiated by investigations with cylinders numbers 7 through 10 described below.

6. The aging response within the temperature range of 700 to 900F is more rapid for cylinders stress relieved at 850F than for those stress relieved at 900F.

Since the results of these investigations indicated that aging properties of flow-turned cylinders are independent of forging techniques within the temperature range investigated (2000 to 1800F), subsequent subscale and full scale cylinders were ring-rolled by the most practical technique.

Four additional cylinders (numbers 7 through 10)were evaluated to determine the effects of variations in flow-turning practice on aging response and ductility in order to be certain that techniques which produced parts without radial growth and with good surface conditions also produce parts with rapid aging response and adequate ductility. Also evaluated was the effect of a 15-minute 1800F solution treatment prior to flow-turning.

The blanks from which cylinders 7 through 10 were flow-turned were forged in two operations at 1900F, annealed and sized at 1450F, and solution treated at 1800F for 15 minutes with a water quench. Between flow-turn passes the cylinders were annealed at 1450 to 1550F and cleaned. Reductions during the second flow-turn passes were 54, 51, 48 and 42 per cent respectively. Cylinders numbers 7, 8, and 10 were stress relieved at 850F for one-half hour before sectioning. Cylinder number 9 was sectioned and cut into specimen blanks in the as-flow-turned condition. These blanks were then clamped between steel plates during a half-hour stress relief at 850F to minimize the specimen curvature.

The aging responses of these cylinders (Tables XXXVII through XL and Figure 56 through 59) show that cylinder number 7, which was reduced 54 per cent during the second pass, had a more rapid aging response than cylinder number 10, which was reduced only 42 per cent during the second pass. The aging response of cylinders numbers 8 and 9 is intermediate between that of cylinders numbers 7 and 10.

Similar to the previously discussed four cylinders, the circumferential tensile strength of cylinders numbers 7 through 10 was approximately 10,000 psi greater than that in the axial direction. Cylinders numbers 7 and 10 exhibited similar levels of ductility at equivalent yield strength levels in the circumferential direction. However, cylinder number 10 exhibited superior ductility in the axial direc-

tion not only to cylinder number 7, but also to cylinders numbers 8 and 9. This superiority was attributed to the improved outer surface condition resulting from the flow-turn machine modifications discussed previously. The notched tensile strengths of cylinders numbers 9 and 10 were similar at equivalent yield strength levels. If the cylinders were aged to the 180,000 psi yield strength level in the axial direction, the anticipated notched strengths would be 155,000 psi in the axial direction and 170,000 psi in the circumferential direction.

Fracture toughness specimens (3 x 12 inches and internally notched) were machined from cylinders numbers 9 and 10 after aging to various yield strength levels. The results from testing these specimens (Table XLI and Figure 60) are in good agreement with the data obtained previously and indicate G_c* values of 600 in-lbs/in^2 at the 180,000 psi yield strength level and 190 in-lbs/in^2 at the 200,000 psi yield strength level. Although 190 in-lbs/in^2 may be considered a marginal level of toughness, it has proven to be sufficient during the full scale burst of a cylinder which failed at a stress of 242,000 psi.

VI EFFECT OF HYDROGEN CONTENT ON MECHANICAL PROPERTIES OF COLD WORKED B-120 VCA TITANIUM ALLOY

High hydrogen contents embrittle many high-strength titanium-base alloys. An investigation was therefore conducted to determine if the maximum hydrogen content encountered in B-120 VCA titanium alloy processing (200 ppm) is responsible for any embrittlement when the alloy is utilized at high strength levels.

A. Inoculation Technique

Three techniques for hydrogenation were investigated. The first technique involved etching in an aqueous solution of hydrofluoric and nitric acid. This technique was unsatisfactory because it produced high hydrogen contents on the surface and intergranular surface attack. The second technique attempted was to expose the alloy to a hydrogen atmosphere at various pressures and temperatures in the range of 400 to 600F. This technique was abandoned because the desired hydrogen contents could not be obtained using reasonable pressures and times. Temperatures higher than 600F could not be used since they would cause the material to age.

The third and most successful technique was a cathodic process employing 15 per cent sulphuric acid in water for the electrolyte, a lead anode, and the titanium alloy for the cathode. The electrolyte was maintained at 130F and low current densities (approximately 0.1 ampere per square inch) were used. The hydrogen contents obtained after various treatment times (Figure 61) demonstrate reasonably good reproducibility. Several test samples were hydrogenated to the 200 ppm hydrogen level, heat treated at 850F for one hour, and analyzed for hydrogen content at various depths in the thickness of the sample. No gradient in hydrogen content was detected indicating that the 850F aging treatment homogenized any variations in hydrogen content produced during hydrogenation.

B. Test Results From Cold-Rolled Sheet and Flow-Turned Stock

The effects of hydrogen on both cold-rolled and flow-turned material were investigated. Initially, specimens blanks were cold-rolled with 50 per cent reduction and then aged at temperatures from 800 to 900F for various times to determine the aging response. Results from testing these specimens (Table XLII) indicated that the 180,000

psi yield strength level could be attained after aging one-half hour at 850F. Based on these results, a number of cold-rolled (50 per cent reduction) specimens cathodically hydrogenated to the 200 ppm hydrogen level and in the as-received condition with 70 ppm hydrogen were aged for one hour at 850F to ensure 180,000 psi minimum yield strength and subsequently tested.

The results of smooth and notched (K_t = 8) tensile testing (Table XLIII and Figure 62) indicate that the specimens with the low hydrogen contents have slightly higher tensile and yield strengths than those with the higher hydrogen content. This slight difference in strength may only be a result of slight variations in processing or it may result from the hydrogen tending to stabilize the beta phase and thereby retard the aging response. The notched (K_t = 8) strength appears to be similar for specimens with the two different hydrogen levels.

The results of notched (K_t = 8) sustained-load testing conducted at temperatures from -40 to 400F (Table XLIV and Figure 63) demonstrate that notched (K_t = 8) specimens can be loaded to stresses slightly below the normal tensile failure stress for periods of at least 150 hours without failure. Only two specimens failed during sustained-load testing. One of these (specimen number 21 of Table XLIV) contained 70 ppm hydrogen and the other (specimen number 11) contained 200 ppm. It appears that these failures resulted from the exceptionally high loads (160,000 and 165,000 psi) which equalled or exceeded the previously determined notched tensile strength for the material, rather than from hydrogen embrittlement.

Contrary to the anticipated results, Figure 63 indicates that the sustained-load strength of material with 70 ppm hydrogen is lower than that of material with 200 ppm hydrogen. To determine the validity of these results, additional sustained-load testing was conducted using stress concentration factors (K_t) of 3 and 6. Results from these tests (Tables XLV and XLVI and Figure 64) indicate no difference in the notched sustained-load strength between specimens with 70 and 200 ppm hydrogen and it appears therefore that the previous results were anomolous.

A similar program was conducted on axially and circumferentially oriented specimens from 14-inch diameter cylinders flow-turned in two passes with 50 per cent reduction per pass. The first of these cylinders had been vacuum annealed at 1400F before flow-turning to reduce the hydrogen content to 70 ppm. The aging response after flow-turning however indicated a generally low level of ductility which was attributed to an inferior inside surface condition (see Table XLVII and Figure 65). The second cylinder was vacuum annealed at 1400F and then re-solution treated at 1800F for 15 minutes and water quenched before flow turning. After flow-turning, axially and circumferentially oriented specimen blanks were machined from the cylinder and the aging response was determined. As expected, the cylinder was found to ha· uperior ductility (Table XLVIII and Figure 66).

Half of the specimens were hydrogenated to the 200 ppm hydrogen level and then all of the specimens were age-flattened at 850F for one-half hour to attain the 180,000 psi minimum yield strength level. The results of tensile testing smooth and notched (K_t = 8) axially oriented specimens at -40 to 400F and smooth and notched circumferentially oriented specimens at 70F appear in Table XLIX and Figure 67. With two minor differences, these results are in excellent agreement with those obtained with cold-rolled and aged material. First, there is considerably more scatter in the notched strength data for flow-turned material than for cold-rolled material. This scatter resulted from the curvature of the specimens which persisted even after the age flattening treatment. Secondly, the hydrogenated and unhydrogenated companion specimens have the same strength, which indicates that the differences in strengths previously noted with cold-rolled material probably resulted from slight differences in the processing sequence.

Bump-up tests (for which the stress is increased 5,000 psi every 5 hours) were conducted on circumferential notched (K_t = 8) specimens at -40 through 400F and on axial notched specimens at 70F. The results (Table L) were used to determine the loads for sustained-load testing.

Subsequent sustained-load test results (Table LI) demonstrated that notched (K_t = 8) specimens prepared from flow-turned material are capable of sustaining loads close to the failure stress for long periods. No specimens failed during sustained loading and the tensile strengths of notched specimens subjected to sustained-

load testing were equivalent to companion specimens which were not subjected to sustained loading (compare Tables LI and XLIX).

This investigation indicated that hydrogen contents of 70 and 200 ppm do not embrittle or impair the load-carrying ability of the subject alloy at the 180,000 psi yield strength level in the temperature range of -40 to 400F.

C. Recommended Acceptance Specification for Hydrogen Content in B-120 VCA Titanium Alloy

Although hydrogen contents as high as 200 ppm have been shown to have no adverse effect on the subject alloy at the 180,000 psi yield strength level, it is recommended that hydrogen contents greater than 150 ppm in B-120 VCA titanium alloy be considered excessive. A maximum content of 150 ppm is recommended by the Titanium Metals Corporation of America and has been used at Pratt & Whitney Aircraft under the subject contract.

VII. FULL SCALE FLOW-TURNING DEVELOPMENT

A. Flow-Turning Practice

Six full scale 40-inch diameter roll-forged rings were provided for this program. Three of the rings were initially intended for further evaluation of the flow-turning practice and adjustment of the parameters as necessary for the larger diameter cylinders. The remaining three were to provide hardware parts machined to design requirements.

On the basis of the 14-inch diameter subscale development, it was decided to use the original 0.062-inch tip radius rollers for the first pass to obtain the best dimensional control and the 0.062-inch modified tip rollers for the second pass to obtain the desired surface finish.

The first two full scale rings were solution heat treated at 1800F for 30 minutes to allow a final evaluation of the effect of the 1800F solution treatment on aging response. The first of these was flow-turned first pass using the final parameters established on subscale 14-inch diameter blanks, that is, a roller feed of 0.020 inch per mandrel revolution per roller, 50 per cent reduction, and approximately 675 feet per minute mandrel surface speed which scaled to a mandrel speed of 52.5 rpm. Unfortunately, the carriage locks slipped under the flow-turning loads, thereby increasing the roller-mandrel gap setting and providing only 31 per cent reduction instead of the intended 50 per cent. The blank was annealed at 1600F, pickled, sized, and returned for completion of the 50 per cent reduction. The blank was flow-turned successfully to the intended wall thickness of 0.145 to 0.155 inch. The flow-turning parameters are shown in Table LII and growth results in Figure 68. The final flow-turning pass would have provided sufficient reduction to achieve the necessary cold working to promote aging to the required strength levels. However, other phases of the motor case program required hoops of flow-turned material so this first cylinder was diverted prior to the final pass.

The second full scale blank was given the first flow-turn pass satisfactorily although the rollers were noticeably misaligned. (Since this program was started prior to completion of the subscale program, the bridged indicator for controlling alignment

had not yet been installed). The feed for this blank, as reported in Table LII, was estimated from the feed lines produced by the rollers. There was essentially no diametral growth on this pass. The cylinder was then prepared for the second pass using the process developed with subscale cylinders. No sizing was required prior to the second pass. The cylinder was mounted on the mandrel and a trial pass was made on the 3.5 inch long test section with a 0.010 feed-reduction parameter. A description of this test section is given in Figure 25. It was found that the test section had decreased in diameter, seizing the blank to the mandrel. To prevent the remaining hardware portion of the cylinder from severely seizing on the mandrel, the effective feed was decreased from 0.020 inch to 0.018 inch per mandrel revolution per roller by increasing the mandrel rpm from 52.5 to 55 and holding the carriage feed constant at 2.1 inches per minute. The feed-reduction parameter was thereby reduced and a small amount of growth would occur as predicted by the unit growth curve. The second full scale blank was thus given the second flow turn pass with satisfactory results. The diametral growth was only 0.023 inch or 0.0006 inches per inch of diameter. A photograph of this cylinder is shown in Figure 69. The 3.5-inch long test section was trimmed off after the cylinder had been stress-relieved at 850F for 30 minutes. The test section provided material for determination of tensile properties. The results of these tensile tests are shown in (Table LIII and in Figure 70). The aging response indicated that this part was capable of attaining a 200,000 psi yield strength level in the circumferential direction with 4 per cent minimum elongation. In the as-stress-relieved condition this part had a minimum yield strength of 180,000 psi with 6 per cent elongation.

Based on the excellent tensile results from subscale cylinders numbers 9 and 10 and the second full scale cylinder, the remaining five full scale roll-forged rings were solution-treated at 1800F for 15 minutes, water quenched, and were machined into flow-turn blanks. Tensile results of specimens from the 40-inch roll-forged rings after re-solution treatment showed that the reduction in area was increased to a range of 49 to 59 per cent (Table LIV), similar to results previously obtained with ring forgings. Reduction in area has been the most significant improvement in tensile properties with this solution treatment. Flow-turning experience in this program has qualitatively indicated that tensile reduction in area is the best measure of flow-turnability of B-120 VCA titanium alloy.

Full scale blanks numbers 2 through 7 were flow-turned first pass. The flow-turning parameters and blank dimensions are shown in

Table LII. The revised operating procedure with the Hydrospin machine utilizing the bridged indicator to control roller alignment was used during the flow-turning of these cylinders.

As noted in Table LII, blank number 3 was reduced in diameter by 0.067-inch during the first pass. Considerable difficulty was encountered in removing this cylinder from the mandrel. The decrease in diameter was caused by the higher flow-turn reduction resulting from less mandrel deflection with the rollers properly aligned. Subsequent blanks were flow-turned with the machine pre-set for less deflection and very little diametral change was noted as a result of flow-turning during the first pass. Diametral growth was only 0.025-inch or less in blanks numbers 4, 5 and 6 corresponding to a unit growth of under 0.0006 inches per inch of diameter.

Blanks numbers 3,4,5 and 6 were then stress relieved at 850F for 30 minutes and a one-half inch test section machined from one end of each blank to provide material both for evaluating annealing temperatures and for specimens to be annealed with the blanks. The four blanks were then annealed at 1500 to 1550F for 30 minutes and air cooled.

The four blanks were vapor-blast cleaned, pickled in an aqueous solution of 3.5 per cent HF (70 per cent concentrate), and 35 per cent HNO_3 to remove 0.003 inch per surface of contaminated (oxygen-rich) material and successfully flow-turned second pass. Since the amount of radial growth during first pass flow-turning was small, no sizing was performed prior to the second pass for any of the full scale blanks. No local bulging occurred during full scale flow-turning and the maximum diametral growth during the second pass was 0.030 inch or a unit growth of 0.0008 inches per inch of diameter.

A summary of the inspection results on completed cylinders 2 through 6 is given in Table LV. The final wall thickness was varied to obtain cylinders for testing at aged strength levels of 180,000 psi, 200,000 psi and 210,000 psi. The wall thickness variation for any one cylinder varied from a minimum of 0.003 inch to a maximum of 0.008 inch. It is significant to note that the data generated and the flow-turning technique developed with subscale cylinders were directly applicable to full scale cylinders so that five out of the six full scale blanks flow-turned were useable as hardware parts and very little full scale development was required.

Based on these results, it should be possible to use the roller configuration and flow-turning techniques developed in this program for flow-turning B-120 VCA titanium alloy cylinders over a wide range of diameters with good dimensional control and with the capability of attaining a minimum yield strength of 200,000 psi with 4 per cent minimum elongation after aging.

B. Aging Response of Burst-Test Components

Test pieces were machined from full scale 40-inch diameter flow-turned cylinders F-4, F-7, and F-2 after the cylinders were stress relieved at 850F for one-half hour. The 800F aging response of F-4 was determined in both the axial and circumferential directions. The data (Table LIII and Figure 70) indicated that the cylinder attained the 180,000 psi yield strength level after stress relieving at 850F for one-half hour and therefore no further aging treatment was given to the cylinder. The tensile properties of the cylinder after burst testing (discussed in section VII-D) indicated that the yield strength in the circumferential direction was considerably higher than anticipated. Since this was attributed to yielding during the sizing operation, the processing sequence for subsequent cylinders was modified so that the sizing operation was conducted before the determination of aging response and subsequent aging. It was also decided to age cylinders to the 200,000 psi minimum yield strength level in the circumferential direction rather than to the 180,000 psi yield strength level in the axial direction.

Since test pieces had already been removed from cylinders F-7 and F-2, circumferential specimens were machined, prestrained 0.35 and 0.40 per cent respectively to simulate the sizing operation, and aged. The aging response data for cylinder F-7 (Table LVI and Figure 71) demonstrated the excellent ductility (5 per cent elongation) of the cylinder at the 200,000 psi yield strength level. Based on the aging response data, an aging treatment of one-half hour at 850F was selected for cylinder F-7 to produce the minimum yield strength level of 200,000 psi in the circumferential direction and maximum tensile yield strength margin. Tensile data for specimens aged with the part are also presented in Table LVI and Figure 71.

The aging response data for cylinder F-2 (Table LVII and Figure 72) indicated that the 200,000 psi minimum yield strength level in the circumferential direction would be attained after aging 45 minutes at 850F and the cylinder was given this treatment.

C. Sizing

Because the flow-turning mandrel was 0.200 inch undersize (0.5 per cent), and since the diametral growth during flow-turning was controlled to within 0.040 inch by the improved flow-turning techniques, the cylinders had to be expanded on sizing clusters to produce a diameter compatible with the motor case end closures.

Sizing presented some problems since the cylinder ends were in the annealed condition and the thin wall section had a high degree of cold working. These two sections therefore expanded at different rates and produced a bell-mouth condition.

Results from burst testing the first cylindrical center segment (F-4) indicated that as a result of the sizing operation the yield strength and ultimate strength coincided. Subsequent investigations led to the conclusions that a spread between the yield strength and ultimate strength could be maintained by sizing before aging, an acceptable procedure since aging does not cause dimensional changes. The physical property uniformity investigation of the second burst-test cylinder (F-7) affirmed the suitability of the modified procedure.

It is concluded that future B-120 VCA titanium alloy cylinders should be flow-turned on a mandrel having a diameter not more than 0.25 per cent below the required finished part inside diameter and that sizing be conducted before the cylinders are aged.

D. Tensile Property Uniformity of Cylinders F-2, F-4, and F-7 After Hydrostatic Testing

Cylinders numbers F-2, F-4, and F-7 were evaluated for tensile property uniformity after burst testing. The results (Tables LVIII through LX) indicate that all of the cylinders exhibited satisfactory uniformity and the desired property minimums of 200,000 psi yield strength with 4 per cent elongation in the circumferential direction.

As mentioned previously, cylinder F-4 exhibited unexpectedly high yield strengths in the circumferential direction. The increased yield strength was attributed to straining in the circumferential direction during sizing since the yield strength and ultimate strength were almost equal. That the straining occurred during sizing and not during testing is apparent since this cylinder burst prematurely at only 540 psig internal oil pressure which corres-

ponds to a hoop stress of 150,000 psi. Failure initiated in a defective girth weld joining the cylinder to the test fixture.

Tests of specimens machined from burst cylinder F-7 which failed at 830 psi g internal oil pressure (approximately 230,000 psi hoop stress) demonstrated that the anticipated circumferential yield strength of 200,000 psi was attained by use of the selected treatment and that little or no yielding occurred prior to failure, since the yield strength of circumferentially oriented tensile specimens after burst was still about 10,000 psi below the ultimate tensile strength. Microstructures of cylinder F-7 (Figures 73 and 74) reveal the extent of the severe deformation which the cylinder received during flow-turning. These microstructures are typical of those for all material flow-turned by the established practice and subsequently stress relieved or aged for short periods at temperatures between 700 and 900F.

Tests of specimens machined from cylinder F-2, which fractured during burst testing at 838 psi g internal oil pressure as the center section of the full scale motor case, exhibited the required strength and ductility. The data disclosed no effect of straining during hydrostatic testing (Table LX). Failure in the full scale case originated in the front closure, although the hoop stress in the cylinder at burst was approximately 240,000 psi.

The post-test analysis of the burst components have demonstrated that the cylinders fabricated by the recommended techniques posses satisfactory property uniformity and attain the 200,000 psi yield strength level with 4 per cent elongation in one inch of gage length.

VI CONCLUSIONS

The smooth and notched (K_t=8) tensile properties of ring-rolled B-120 VCA titanuim alloy which has been solution treated at 1450F for 30 minutes or at 1800F for 15 minutes and water quenched are independent of the ring-rolling practice within the range of techniques investigated (single or multiple rolling operations at temperatures between 1800 and 2000F). However, the tensile properties may be sensitive to the amount of reduction and the first rings made by a new practice should be fully evaluated.

The flow-turnability of ring-rolled B-120 VCA titanium alloy, as determined by the quality of cylinders formed in two passes (50 per cent reduction each pass) with an intermediate annealing treatment, is also independent of the rolling technique within the range investigated, but is highly dependent on the post-rolling solution treatment. Optimum flow-turnability can be achieved by solution treating at 1800F for 15 minutes and water quenching. This treatment increases the tensile reduction of area to approximately 50 per cent.

The recommended processing sequence for fabricating 14- or 40-inch diameter cylinders with a thickness of 0.070 inch, a minimum circumferential yield strength of 200,000 psi, and a minimum tensile elongation of 4 per cent in one inch, is as follows:

1. Ring roll in single or multiple operations at temperatures between 1800 and 2000F,
2. Solution treat at 1800F for 15 minutes and water quench,
3. Flow-turn with approximately 50 per cent reduction,
4. Anneal at a temperature between 1450 and 1500F for 30 minutes and air cool,
5. Flow-turn with approximately 50 per cent reduction,
6. Stress-relieve at 850F for 30 minutes and air cool
7. Age at 800F, if necessary, for the time required to produce the desired strength level.

Forty-inch diameter cylinders produced by the recommended process and aged to a minimum circumferential yield strength of 200,000 psi

exhibited excellent performance during hydrostatic testing. Three cylinders were tested under the subject contract. One of these sustained a maximum circumferential membrane stress of 246,000 psi and exhibited a 0.2 per cent yield strength of 215,000 psi. The second, tested as part of a complete case, sustained a stress of 212,000 psi when failure occurred in the front closure of the case. The third cylinder failed prematurely through a weld defect so that significant data for the flow-turned section was not obtained.

Parabolic contoured rollers provide considerably better dimensional control for flow-turning B-120 VCA cylinders than did the conically shaped rollers normally used with steel.

A correlation of the unit diamentral growth to the product of the per cent reduction and the roller feed per unit mandrel speed has been established in conjuction with the design of parbolic rollers. These parameters permit excellent dimensional control during the flow-turning of B-120 VCA titanium alloy cylinders with a wide variety of diameters.

The methods used in correlating flow-turning parameters and modifying the roller design should be useful in the development of successful flow-turning practices for other titanium alloys.

APPENDIX A

Tables

TABLE I

Textures Observed in B-120 VCA Titanium Alloy Sheet and Flow-Turned Cylinder

Condition	Principle Texture Components
Mill Annealed Sheet	Essentially Random
Cold Rolled Sheet	$(100)\ [011]$ and $(111)\ [1\bar{1}0]$
Flow-Turned Cylinder	
a) Inner Section	$(100)\ [011]$ and $(111)\ [11\bar{2}]$
b) Outer Section	$(\bar{1}11)\ [11\bar{2}]$

TABLE II

Tensile Properties of Cold-Rolled Sheet and Flow-Turned Cylinders of B-120 VCA Titanium Alloy with Respect to Direction and Thickness

1. Cold Rolled Sheet*

Direction	Age	Test Area	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)
longitudinal	800F(1) AC	total thickness	184.0	178.0	8.0
	"	"	187.7	181.0	8.0
"	800F(2) AC	"	193.0	187.0	7.0
"	"	"	188.0	180.0	9.0
"	800F(4) AC	"	233.0	225.0	3.0
"	"	"	210.0	202.0	7.0
transverse	800F(1) AC	"	195.0	182.5	6.0
"	"	"	196.0	182.0	6.0
"	800F(2) AC	" "	198.5	187.5	5.0
	"	"	197.0	186.0	4.0
"	800F(4) AC	"	215.0	204.5	5.0
"	"	"	216.0	204.0	5.0

2. Flow-Turned Cylinder**

Direction	Age	Test Area	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)
axial	850F(1/2) AC	total thickness	187.5	180.5	6.5
"	"	"	187.0	181.8	5.0
circumferential	"	"	199.0	190.0	5.5
"	"	"	204.8	-	5.5
"	"	outside half of wall thickness	208.8	202.0	2.5
"	"	"	193.8	190.2	[illegible].0
axial	"	inside half of wall thickness	192.8	187.6	4.0
"	"	"	188.2	182.0	3.5
circumferential	"	"	177.4	176.0	5.0
"	"	"	184.6	178.8	3.5

*Cold-rolled to fifty per cent reduction in multiple passes to 0.065-inch final thickness
** Flow-turned to fifty per cent reduction in single pass to 0.070-inch thickness

TABLE III

Fracture Toughness (G_c)* Test Results on B-120 VCA Titanium Alloy
Pershing Flow-Turned Cylinders Numbers 1 and 2

Cylinder Number	Direction	Heat Treatment	Average** 0.2% Tensile Yield (ksi)	Net Section Stress (ksi)	G_c (in-lbs/in^2)
1	axial	850F(1/2) AC	181.1	107.0	625
"	"	"		115.0	681
"	circumferential	"	190.0	75.8	297
"	"	"		78.5	327
2	axial	"	185.4	96.8	488
'	axial	"		135.5	962
"	circumferential	'	189.3	73.5	319
"	axial	850F(1/2) AC + 800F(1) AC	191.5	77.3	315
	"	"		73.0	280
	circumferential	"	200.4	61.8	203
.	axial	850F(1/2) AC + 800F(2) AC	205.0	63.0	210
"	"	"		67.8	247
"	circumferential	"	224.3	59.0	181

*3"x12" internally notched specimen with machined notch radii of less than 0.001 inch
**average of two results

Note: Flow-turned cylinders were 40 inches in diameter and 0.080 inch thick.

TABLE IV

Fracture Toughness (G_c) Test Results of B-120 VCA Titanium Alloy Flow-Turned Pershing Cylinder Number 2 showing Effect of Specium Size

Specimen	Net Section Stress (ksi)	G_c (in-lbs/in^2)	G_c* (in-lbs/in^2)
3 x 12 inch internally-notched	80.9	347	365
	89.2	421	449
2 x 8 inch externally-notched	91.3	292	314
	92.5	299	323
	97.4	330	360
1 x 4 inch externally-notched	133.0	305	363
	120.4	250	288
	126.5	276	323

Specimens machined in axial direction after aging at 850F for 30 minutes to average yield strength of 185,400 psi.

G_c^* corrected for plastic straining at notches

Note: Flow-turned cylinders were 40 inches in diameter and 0.080 inch thick.

TABLE V

Modified Charpy Impact Test Results on 40-Inch Diameter Flow-Turned Cylinders Numbers 1 and 2 Tested at -35 to 400F

Cylinder Number	Heat Treatment	Direction	Average* 0.2% Yield Strength (ksi)	Energy Absorption (ft-lbs) -35F	70F	215F	400F
1	850F(1/2)AC	axial	181.2	1.3	1.2	--	--
				1 3	--	--	--
1	850F(1/2)AC	circumferential	190.0	1.3	2.0	--	--
				1.8	1.6	--	--
2	850F(1/2)AC	axial	185.4	1.5	2.0	2.0	3.5
				--	1.2	2.3	3.3
				--	2.0	2.3	3.5
				--	1.5	--	--
				--	1.3	--	--
				--	1.3	--	--
2	850F(1/2)AC	circumferential	189.3	1.3	1.2	2.0	2.5
				--	2.3	1.8	2.5
				--	1.0	2.3	--
				--	1.5	--	--
				--	1.5	--	--
2	850F(1/2)AC +800F(1)AC	axial	191.5	1.0	1.2	1.5	2.5
				1.3	1.2	1.8	2.5
				--	1.0	2.0	3.0
				--	1.3	--	--
				--	1.3	--	--
2	850F(1/2)AC +800F(1)AC	circumferential	200.4	--	0.8	1.8	1.8
				--	1.5	1.8	1.8
				--	1.5	1.8	--
				--	1.3	--	--
				--	1.0	--	--
2	800F(1/2) AC +80G(2)AC	axial	205.0	1.5	1.3	1 5	2.0
				--	2.3	1.5	2.3
				--	1.0	--	2 3
				--	1.0	--	--
				--	1.0	--	--
				--	1.3	--	--
2	850F(1/2)AC +800F(2)AC	circumferential	224.3	1.0	2.0	1.5	1 8
				1.0	2.0	1.5	1.8
				--	1.3	--	--
				--	1.5	--	--
				--	1.3	--	--

*Average of two results

TABLE VI

Instrumented Bend Test Results from 40-Inch Diameter Flow-Turned Cylinders Numbers 1 and 2

Cylinder Number	Heat Treatment	Direction	Average* Yield Strength (ksi)	Instrumented Bend Parameter ($\sigma_m - \sigma_I$)** (psi)
1	850F(1/2)AC	axial	181.2	5,060
				5,200
				11,800
				13,100
1	850F(1/2)AC	circumferential	190.0	10,550
				11,700
2	850F(1/2)AC	axial	185.4	21,800
				21,000
				22,000
				25,700
				15,600
				21,100
2	850F(1/2)AC	circumferential	189.3	9,050
2	850F(1/2)AC +800F(1)AC	axial	191.5	608
				4,020
				1,760
				8,500
2	800F(1/2)AC +800F(2)AC	axial	205.0	820
				1,280
				2,560
				268
				2,640
2	850F(1/2)AC +800F(2)AC	circumferential	224.3	5,500
				2,830

*Average of two results

** σ_m equals maximum stress during bending.

σ_I equals stress at initiation of rapid crack progression.

TABLE VII

Procedure Employed For Rolling Subscale
14-Inch Diameter Rings

Ring Number	Rolling Operation	Furnace Temperature (°F)	Wall Thickness* After Rolling (Inches)	Reduction (Per Cent)
1	Single Operation	2000	**	**
2	Single Operation	1900	**	**
3	Single Operation	1800	**	**
4	First	2000	1 5/8	36.6
	Second	1900	1 1/2	7.7
	Third	1800	1 3/8	9.1
5	First	1900	1 9/16	48.8
	Second	1900	1 3/8	12.0
6	First	1900	1 3/4	31.6
	Second	1800	1 3/8	21.4

*Wall Thickness Before Rolling was 2 9/16 inches

**These Data Are Not Available

TABLE VIII

Tensile Properties of 14-Inch Diameter Rings Numbers
1, 2, and 3 Rolled at Ladish and Heat Treated (1450F(1/2)WQ)

Ring Number	Sample Location	Specimen	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction of Area (Per Cent)
1	1	Smooth	136.4	135.7	124.2	17.0	3. 6
1	2	Smooth	133.9	133.0	120.0	16.0	32.4
1	8	Smooth	134.0	133.5	125.2	17.0	33.2
1	7	Smooth	133.9	132.7	120.0	17.0	32.0
1	3	Notched	186.2	-	-	-	-
1	4	Notched	195.6	-	-	-	-
1	6	Notched	190.8	-	-	-	-
1	5	Notched	197.8	-	-	-	-
2	1	Smooth	136.0	135.4	123.0	15.0	33.0
2	2	Smooth	134.8	133.8	122.9	18.5	33.9
2	8	Smooth	132.4	131.6	119.9	21.0	35.2
2	7	Smooth	136.4	135.6	125.6	16.0	39.6
2	3	Notched	212.4	-	-	-	-
2	4	Notched	209.2	-	-	-	-
2	6	Notched	210.0	-	-	-	-
2	5	Notched	211.8	-	-	-	-
3	1	Smooth	136.2	134.9	125.8	17.0	40.4
3	2	Smooth	137.0	135.0	126.5	20.0	45.0
3	8	Smooth	136.9	135.5	125.0	14.8	35.0
3	7	Smooth	135.5	135.0	124.8	17.2	39.2
3	3	Notched	214.2	-	-	-	-
3	4	Notched	213.6	-	-	-	-
3	6	Notched	206.0	-	-	-	-
3	5	Notched	214.0	-	-	-	-

Dimensions of notched specimens: 0.500 inch major gage diameter, 0.365 inch minor gage diameter at notch, 0.002 inch radius -60° notch

TABLE IX

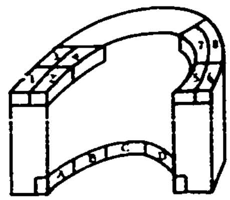
Tensile Properties of 14-Inch Diameter Roll-Forged Rings Numbers 1, 2, and 3 After Annealing at 1450F for 30 Minutes

Ring Number	Specimen Direction	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation - 1" (Per Cent)	Reduction in Area (Per Cent)
1	Circ.	133.4	133.0	122.0	18.0	46.9
1	"	132.0	131.8	122.4	17.2	44.4
1	"	131.0	129.5	121.0	18.8	43.8
1	"	134.0	133.6	123.4	21.2	43.2
2	"	134.0	133.2	126.4	17.2	36.4
2	"	130.6	127.2	116.0	14.8	35.2
2	"	131.6	129.4	119.7	12.0	41.2
2	"	134.4	133.8	124.0	22.8	45.4
3	"	134.4	133.4	119.2	17.2	43.6
3	"	133.0	132.6	119.2	21.2	51.0
3	"	131 5	130 4	120 4	14.8	34 6
3	"	133.6	133.2	124.4	22.8	53.8
1	Axial	134.6	129.0	115.0	18.6	38.0
1	"	134.6	130.9	122.2	22.8	51.0
1	"	136.0	128.4	115.5	20.0	46.8
1	"	133.2	129.2	120.0	20.0	44.6
2	"	132.4	122.5	108.5	21.2	34.6
2	"	135.6	135.0	133.0	13.2	29.4
2	"	136.4	135.8	104.9	16.0	35.0
2	"	137.0	127.8	127.2	17.2	38.2
3	"	141.2	140.4	130.0	17.2	52.7
3	"	137.5	137.0	128.4	20.0	51.8
3	"	139.4	138.9	128.8	24.0	55.0
3	"	139.4	138.2	130.8	21.2	52.8

* Specimens equally spaced around ring.

TABLE X

Tensile Properties
of Subscale 14-Inch Diameter Roll-Forged Rings Numbers 4, 5 and 6
after Annealing at 1450F for 15 Minutes



Ring Number	Sample Location	Specimen	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
4	1	Smooth	131.8	130.1	19.0	36.5
4	2	Smooth	132.4	130.6	20.0	38.0
4	5	Smooth	132.2	130.6	19.0	36.0
4	6	Smooth	134.3	131.8	17.0	36.5
4	3	Notched (K_t=8)	179.0			
4	4	Notched (K_t=8)	197.0			
4	7	Notched (K_t=8)	203.0			
4	8	Notched (K_t=8)	20[illegible].0			
5	1	Smooth	134.4	132.5	17.0	35.5
5	2	Smooth	136.0	133.9	17.0	39.0
5	5	Smooth	134.7	132.9	17.0	35.5
5	6	Smooth	136.3	134.4	17.0	35.5
5	3	Notched (K_t=8)	204.5			
5	4	Notched (K_t=8)	197.0			
5	7	Notched (K_t=8)	203.3			
5	8	Notched (K_t=8)	183.5			
6	1	Smooth	134.8	133.0	17.0	33.0
6	2	Smooth	137.2	135.8	17.0	34.0
6	5	Smooth	133.9	132.3	17.0	36.5
6	6	Smooth	136.2	134.4	18.0	40.5
6	3	Notched (K_t=8)	189.9			
6	4	Notched (K_t=8)	202.0			
6	7	Notched (K_t=8)	205.0			
6	8	Notched (K_t=8)	207.0			
4	A	Smooth	1[illegible]4.4	131.8	21.0	40.0
4	B	Smooth	132.8	130.0	16.5	40.0
4	C	Smooth	133.9	131.0	18.5	40.0
4	D	Smooth	130.7	129.3	18.5	40.0
5	A	Smooth	131.0	128.2	18.5	34.0
5	B	Smooth	130.7	128.5	14.5	34.0
5	C	Smooth	132.0	130.[illegible]	21.0	37.0
5	D	Smooth	130.4	129.[illegible]	16.0	38.0
6	A	Smooth	133.3	130.8	14.5	36.0
6	B	Smooth	130.5	127.8	[illegible]1.0	38.0
6		Smooth	132.[illegible]	[illegible]30.5	20.0	38.0
6	D	Smooth	132.0	130.5	20.0	[illegible]4.0

TABLE XI

Circumferential Tensile Properties of 14-Inch Diameter Roll-Forged Rings Numbers 1, 2, and 3 After Annealing at 1450F and Aging at 900F

Ring Number	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
1	900F(12)AC	166.8	159.0	151.8	4.0	11.2
2	"	168.6	156.8	134.8	5.2	13.0
3	"	167.8	157.2	147.4	5.2	13.5
1	900F(48)AC	197.0	189.0	185.0	2.0	4.2
2	"	201.8	190.6	187.2	3.0	7.2
3	"	197.2	189.4	182.4	2.8	4.2
1	900F(64)AC	208.4	193.8	183.4	2.8	5.2
2	"	203.8	189.5	175.0	2.0	5.2
3	"	202.2	188.6	169.4	2.8	5.4
1	900F(72)AC	204.2	196.4	188.8	1.4	4.0
2	"	208.8	190.0	179.8	2.8	8.8
3	"	200.0	193.6	188.2	1.0	1.4

TABLE XII

Rolling Sequence for Ten Subscale 14-Inch Diameter Rings

Ring Number	Pass Number	Temperature (°F) Furnace	Temperature (°F) Finish	Approximate Reduction (Per Cent)
1	1	1900	1610	48.0
2	1	1900	1650	11.0
2	2	1900	--	33.0
3	1	1900	1710	5.0
3	2	1900	--	41.0
4	1	1900	1750	10.0
4	2	1900	--	33.0
5	1	1900	1620	48.0
6	1	1900	1630	48.0
7	1	1900	1650	48.0
8	1	1900	1650	48.0
9	1	1900	1620	48.0
10	1	1900	1660	48.0

TABLE XIII

Ladish Tensile Properties of Subscale 14-Inch Diameter
Rolled Ring Test Material After Annealing at 1450F

Solution Treatment	Ring Number	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
1450F(1/4)WQ	1	135.6	127.4	11.0	26.0
1450F(1/4)WQ	1	134.8	128.0	12.0	24.0
1450F(1/4)WQ	2	136.0	128.6	9.0	20.0
1450F(1/4)WQ	2	136.8	129.6	9.5	21.0
1450F(1/4)WQ	3	135.2	128.4	14.0	29.0
1450F(1/4)WQ	3	135.6	129.8	15.5	27.0
1450F(1/4)WQ	4	133.2	131.6	12.0	26.0
1450F(1/4)WQ	4	131.8	130.4	13.0	29.5
1450F(1/4)WQ	5	134.8	132.5	12.5	27.8
1450F(1/4)WQ	5	136.0	129.8	17.0	30.0
1450F(1/4)WQ	6	134.2	127.6	11.0	23.5
1450F(1/4)WQ	6	133.5	130.2	10.0	25.7
1450F(1/4)WQ	7	135.2	126.4	15.0	23.9
1450F(1/4)WQ	7	134.5	126.3	13.5	25.8
1450F(1/4)WQ	8	132.0	131.2	11.0	24.9
1450F(1/4)WQ	8	134.3	131.9	11.0	24.2
1450F(1/4)WQ	9	135.0	127.2	10.0	26.5
1450F(1/4)WQ	9	135.5	133.0	12.5	26.7
1450F(1/4)WQ	10	134.6	132.4	13.0	32.8
1450F(1/4)WQ	10	136.6	128.5	13.0	32.4
1450F(1/2)WQ	4	136.0	131.6	15.0	33.0
1450F(1/2)WQ	4	136.5	130.8	16.0	32.0
1450F(1/2)WQ	9	134.6	131.4	20.0	42.0
1450F(1/2)WQ	10	136.3	131.2	18.5	40.0

TABLE XIV

Tensile Properties of Full Scale 40-Inch Diameter Ring Samples After Various Heat Treatments

Heat Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
As Received (Annealed)	137.5 ksi	123.3	13.5	35.0
As Received (Annealed)	137.4	125.3	15.0	37.5
As Received (Annealed)	195.3	Notched (K_t = 8)		
As Received (Annealed)	196.0			
1200F(2)WQ	138.8	126.0	3.5	11.0
1200F(2)WQ	139.4	127.5	3.5	16.0
1200F(2)WQ	120.4	Notched (K_t = 8)		
1200F(2)WQ	122.4			
1400F(2)WQ	136.7	125.7	16.0	34.0
1400F(2)WQ	136.2	126.2	13.5	32.0
1400F(2)WQ	201.5	Notched (K_t = 8)		
1400F(2)WQ	19[illegible].0			
1800F(2)WQ	136.4	124.7	18.0	49.0
1800F(2)WQ	136.5	124.3	14.5	52.5
1800F(2)WQ	207.5	Notched (K_t = 8)		
1800F(2)WQ	214.0			
2000F(2)WQ	135.8	123.9	9.0	29.0
2000F(2)WQ	135.0	122.6	8.5	28.8
2000F(2)WQ	161.0	Notched (K_t = 8)		
2000F(2)WQ	183.0			
1400F(2)FC	134.4	125.3	11.0	28.0
1400F(2)FC	133.4	123.8	11.0	27.0
1400F(2)FC	195.8	Notched (K_t = 8)		
1400F(2)FC	189.8			
1800F(2)FC	138.0	123.7	12.0	34.5
1800F(2)FC	136.3	122.3	12.0	36.8
1800F(2)FC	197.0	Notched (K_t = 8)		
1800F(2)FC	198.0			
2000F(2)FC	138.0	126.0	3.5	8.0
2000F(2)FC	136.[illegible]	126.1	3.0	10.5
2000F(2)FC	133.5	Notched (K_t = 8)		
2000F(2)FC	[illegible]58.[illegible]			

TABLE XV

Tensile Properties of Full Scale 40-Inch Diameter
Ring Samples After Various Heat Treatments and Subsequent Aging at 900F

Heat Treatment	Aging Time at 900F (Hours)	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
As Received (Annealed)	64	192.8	175.8	3.5	5.8
As Received (Annealed)	72	191.4	180.7	2.5	1.8
As Received (Annealed)	96	203.4	188.5	2.5	4.4
1400F(2)WQ	64	174.7	161.1	2.0	3.5
1400F(2)WQ	72	190.1	186.5	2.0	1.0
1400F(2)WQ	96	197.9	188.0	2.0	3.0
1800F(2)WQ	64	196.8	179.5	4.0	7.5
1800F(2)WQ	72	198.2	176.4	4.0	7.0
1800F(2)WQ	96	206.0	187.2	3.5	5.5
2000F(2)WQ	64	192.5	178.7	3.0	5.0
2000F(2)WQ	72	199.5	186.2	2.0	2.5
2000F(2)WQ	96	193.4	178.5	2.0	2.3
1400F(2)FC	64	165.2	150.5	3.0	4.5
1400F(2)FC	72	176.6	162.3	2.5	1.8
1400F(2)FC	96	189.9	176.8	2.5	1.0
1800F(2)FC	64	155.2	141.2	6.5	9.5
1800F(2)FC	72	181.8	161.8	3.5	5.0
1800F(2)FC	96	164.0	147.3	6.0	8.5
2000F(2)FC	64	169.0	158.3	2.0	1.0
2000F(2)FC	72	176.8	180.4	2.0	2.0
2000F(2)FC	96	193.3	189.4	2.5	1.0

TABLE XVI

Rolling Sequence for Eight Full Scale 40-Inch Diameter Rings

Ring Number	Pass Number	Mandrel Diameter (Inch)	Temperature* (°F) Start	Temperature* (°F) Finish	Finish Dimensions (Inch) Inside Diameter	Finish Dimensions (Inch) Wall Thickness	Reduction in Area (Per Cent)
1**	1	5	1850F	1700F	11	3 3/4	6.3
2	1	10	1850	1600	12 1/2	3 5/8	9.4
	2	8	1800	1625	16	3	17.3
	3	8	1860	1610	20	2 3/4	8.4
	4	8	1875	1560	38 3/8	1 1/2	45.5
3	1	5	1850	1300	14	3 1/4	18.8
	2	10	1860	1680	18 3/8	3	7.7
	3	8	1860	1650	21 3/4	2 3/8	20.8
	4	8	1880	1650	38 1/4	1 1/2	36.9
4	1	7	1850	1400	--	3 3/8	15.6
	2	7	1845	1500	--	2 15/32	25.9
	3	7	1845	1650	30 1/4	2	20.0
	4	8	1890	1695	38 1/4	1 1/2	33.3
5	1	7	1845	1530	--	3 3/8	15.6
	2	7	1850	1550	--	2 3/8	29.5
	3	7	1850	1530	30 3/4	2	15.8
	4	8	1890	1620	36 11/16	1 5/16	34.4
6	1	7	1845	1400	--	3 3/8	15.6
	2	7	1880	1500	--	2 5/8	22.2
	3	7	1850	1500	23 1/2	2 7/16	8.2
	4	8	1890	1695	38 1/4	1 1/2	38.5
7	1	7	1840	1510	--	3 3/8	15.6
	2	7	1810	1400	--	3 1/8	7.4
	3	7	1880	1500	20 1/2	2 1/2	20.0
	4	8	1885	1560	38 1/4	1 1/2	40.0
8	1	7	1840	1510	--	3 3/8	15.6
	2	7	1810	1400	--	3 1/8	7.4
	3	7	1880	1500	20 1/2	2 1/2	20.0
	4	8	1885	1560	38 1/4	1 1/2	40.0

* Furnace temperature of 1900F, all rings water-quenched from rolls after each pass.
** Ruptured axially and circumferentially during first pass.

TABLE XVII

Tensile Properties of Full Scale 40-Inch Diameter Rings Rolled By Ladish, Solution-Treated at 1450F for 30 Minutes and Water-Quenched

Ring Number	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)	Notched Tensile Strength (K_t = 8, ksi)
2	131.6	131.1	122.3	21.5	39.0	205.0
2	132.0	129.6	122.0	18.5	43.0	208.0
3	132.0	130.3	124.0	22.0	41.5	211.0
3	133.2	129.6	121.4	20.0	40.5	211.5
4	132.3	129.3	121.4	18.0	36.0	209.0
4	133.0	128.7	122.2	20.0	40.5	209.0
5	133.5	130.8	120.6	17.5	33.5	209.0
5	133.2	130.3	122.0	20.0	35.5	209.5
6	133.2	130.5	123.5	20.0	40.5	209.0
6	139.0	126.4	121.3	15.0	40.5	204.0
7	136.3	126.5	120.0	15.0	43.5	213.5
7	137.2	125.8	118.7	15.0	45.0	210.5
8	138.3	127.0	121.3	15.0	39.0	209.5
8	140.0	130.0	123.2	16.0	40.0	211.0

TABLE XVIII

Ladish Tensile Properties of Full Scale 40-Inch
Diameter Rings Rolled in Multiple Operations at 1900F
and Solution-Treated at 1300-1800F

Ring Number	Solution Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)
2	1300F(1/2)WQ	135.1	126.5	15.5	30.6
"	1450F(1/2)WQ	135.1	126.1	17.5	38.3
"	1800F(1/4)WQ	135.9	127.9	19.5	56.1
5	1300F(1/2)WQ	134.2	125.6	11.5	24.8
"	1450F(1/2)WQ	133.2	124.4	18.0	35.4
"	1800F(1/4)WQ	135.4	126.0	21.0	53.6
7	1300F(1/2)WQ	132.5	126.0	15.0	38.0
"	1450F(1/2)WQ	132.9	125.5	15.5	35.7
"	1800F(1/4)WQ	135.3	126.3	21.5	57.1

TABLE XIX

Axial Tensile Properties of Subscale 9.4-Inch Diameter Cylinders Flow-Turned in Two Passes (50% Reduction Per Pass)*

Processing Sequence	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)
1830(1/2)WQ+Flow-Turn+850(1/2)	218.0	206.6	1.0
" " " "	215.0	204.0	2.5
" " " " +800(1/2)	220.3	208.5	1.5
" " " " "	220.3	208.0	3.5
" " " " +800(1)	210.0	197.2	4.5
" " " " "	213.5	201.8	5.5
" " " " +800(2)	227.5	214.5	2.0
" " " " "	222.3	210.5	2.0
" " " " +800(4)	226.5	212.5	1.5
" " " " "	219.0	211.0	1.5
" " " " +800(8)	213.0	--	--
Flow-Turn** +850(1/2)	199.0	189.9	6.0
" " "	202.5	196.1	6.0
" " " +800(1/2)	203.5	195.0	4.0
" " " "	208.5	197.7	5.0
" " " +800(1)	212.5	203.5	3.0
" " " "	213.0	204.5	2.0
" " " +800(2)	220.0	208.5	4.0
" " " "	222.0	214.0	3.5
" " " +800(4)	227.0	213.0	3.5
" " " "	230.5	215.0	3.5
" " " +800(8)	247.5	233.0	1.0

* Flow-turn blanks fabricated by rolling and axially welding 0.375-inch thick plate stock.

** Flow-turned in mill-annealed condition.

TABLE XX

Tensile Properties of 40-Inch Diameter Roll-Forged Rings
Re-Solution Treated at 1800F for Fifteen Minutes and Water Quenched

Ring Number	Tensile Strength (ksi)	0.2%-Yield Strength (ksi)	Elongation-1" (Per Cent)	Reduction (Per Cent)	Notched Tensile Strength (K_t=8, ksi)
2	134.8	125.7	25	59	211.0
2	138.3	126.9	20	54	212.0
3	137.2	126.5	19.5	50.5	209.0
3	138.0	127.3	21.5	49	217.2
4	129.0	125.8	24.5	49.5	209.0
4	128.7	127.6	25.5	50.5	208.0
5	128.5	127.0	25.0	43.5	204.5
5	127.0	126.0	25.0	48.5	207.0
6	136.3	---	21.5	49	211.5
6	136.3	127.0	24.0	59	218.8
7	136.5	125.6	20	57.5	216.0
7	146.3	---	18.5	57.5	216.0
8	139.0	---	21.0	59.5	216.0
8	143.5	129.5	18.5	51.0	211.5

1

Flow-Turning Parameters and Dimensions

Cylinder Number	Inside[(1)] Diameter Before Flow-Turning (Inches)	Wall Thickness Before Flow-Turning (Inches)	Mandrel Speed (RPM)	Roller Feed (Inches / Min / Roller)	Red (Pe
1 (9.4" Dia)	9.406-9.410	0.306-0.308	385	6.15	4
2 (9.4" Dia)	9.410	0.301-0.302	385	6.15	4
3 (14" Dia)	14.134-14.136	0.324-0.325	260	4.15	5
4 (14" Dia)	14.134-14.135	0.323-0.325	260	4.15	4
5 (14" Dia)	14.132-14.135	0.324	260	4.15	4
6 (14" Dia)	14.129-14.134	0.303	260	4.15	4
7 (40" Dia)	39.623-39.627	0.252	90	1.5	4
8 (40" Dia)	39.623-39.627	0.258-0.262	90	1.5	5
1 (9.4" Dia)	9.426- 9.436	0.155-0.160	385	6.15	[illegible]
2 (9.4" Dia)	9.410- 9.425	0.144-0.148	385	6.15	[illegible]
3 (14" Dia)	14.115-14.155	0.159-0.163	168	2.7	[illegible]
4 (14" Dia)	14.115-14.150	0.162-0.165	168	2.7	[illegible]
5 (14" Dia)	14.105-14.155	0.162-0.166	168	2.7	[illegible]
6 (14" Dia)	14.090-14.185	0.158-0.160	168	2.7	[illegible]
7 (40" Dia)	39.608-39.696	0.130-0.140	(6)		
8 (40" Dia)	39.580-39.638	0.122-0.135	60	1.0	[illegible]

(1) Use minimum inside diameter to calculate diametral growth
(2) Use maximum inside diameter to calculate diametral growth
(3) Feed-reduction parameter equals (roller feed/mandrel speed) (per cent reduction
(4) Diametral growth equals (final diameter-initial diameter)/initial diameter
(5) Not measured
(6) Cylinder failed during shrinking between flow-turn passes

2

TABLE XXI

ers and Dimensions of Subscale 9.4-Inch, 14-Inch, and Full Scale 40-Inch Diameter Cylinders

First Flow-Turn Pass

Roller Feed (s / Min / Roller)	Reduction (Per Cent)	Wall Thickness After Flow-Turning (Inches)	Inside(2) Diameter After Flow-Turning (Inches)	Feed-Reduction(3) Parameter (Inches/Rev/Roller)	Diametral(4) Growth (Inches / Inch)
6.15	49.0	0.155-0.160	9.414- 9.525	0.00780	0.01260
6.15	48.4	0.144-0.148	9.413- 9.485	0.00774	0.00797
4.15	50.0	0.159-0.163	14.149-14.351	0.00798	0.0154
4.15	49.6	0.162-0.165	14.138-14.228	0.00792	0.00668
4.15	49.4	0.162-0.166	14.146-14.322	0.00788	0.01340
4.15	47.7	0.158-0.160	14.150-14.250	0.00760	0.00856
1.5	46.0	0.130-0.140	39.640-39.862	0.00767	0.00603
1.5	50.5	0.122-0.135	39.655-39.806	0.00842	0.00462

Second Flow-Turn Pass

6.15	50.0	0.076-0.079	(5)	0.00800	-----
6.15	51.0	0.069-0.070	(5)	0.00814	-----
2.7	53.5	0.070-0.080	14.157-14.469	0.00860	0.0250
2.7	53.0	0.074-0.080	14.270-14.459	0.00853	0.0244
2.7	55.0	0.071-0.076	14.094-14.519	0.00885	0.0293
2.7	50.0	0.080-0.082	14.122-14.250	0.00805	0.0114
1.0	33.0	0.080-0.085	39.820-39.840	0.00550	0.00657

) (per cent reduction/100)
tial diameter

1

TABLE XXI

Flow-Turning Parameters and Dimensions of Sul
(Rolled and Welded 0.375-In

Single Roller Mac

First Flow-Turn

Cylinder Number	Inside Diameter Before Flow-Turning (inches)	Wall Thickness Before Flow-Turning (inches)	Mandrel Speed (RPM)	Roller Feed (inches/min/roller)	Redu (Perc
1	9.408	0.300	320	5	25
2	9.408	0.280	280	3.5	38
3	9.406	0.232	280	3.5	44
4	9.408	C.225	280	3.5	42
5	9.411	0.300	315	4.5	25
6	9.408	0.267	280	4.5	42
7	9.404	0.230	300	6	43.
8	9.408	0.300	300	6	38.

Second Flow-Turn

Cylinder Number	Inside Diameter Before Flow-Turning (inches)	Wall Thickness Before Flow-Turning (inches)	Mandrel Speed (RPM)	Roller Feed (inches/min/roller)	Redu (Perc
3	9.437	0.127 - 0.132	280	3.5	63
4	9.443	0.127 - 0.132	280	3.5	54
6	9.442	0.155	280	4.5	60
7	9.425	0.127 - 0.132	300	6	43
8	9.430	0.182 - 0.187	300	4.5	69

(1) Feed-reduction parameter equals (roller feed/mandrel speed) (per cent reduction/100)
(2) Diametral growth equals (final diameter-initial diameter)/initial diameter
(3) Failed during first pass

2

TABLE XXII

rameters and Dimensions of Subscale 9.4-Inch Diameter Cylinders (Rolled and Welded 0.375-Inch Plate Stock)

Single Roller Machine

First Flow-Turn Pass

Roller Feed (inches/min/roller)	Reduction (Percent)	Wall Thickness After Flow-Turning (inches)	Inside Diameter After Flow-Turning (inches)	Feed-Reduction Parameter (1) (inches/rev./roller)	Diametral Growth (2) (inches/inch)
5	25	(3)			
3.5	38	(3)			
3.5	44	0.127 - 0.132	9.437	0.0055	0.00330
3.5	42	0.127 - 0.132	9.443	0.00525	0.00372
4.5	25	(3)			
4.5	42	0.155	9.442	0.00675	0.00361
6	43.5	0.127 - 0.132	9.425	0.0087	-0.00223
6	38.3	0.182 - 0.187	9.430	0.00765	-0.00234

Second Flow-Turn Pass

Roller Feed (inches/min/roller)	Reduction (Percent)	Wall Thickness After Flow-Turning (inches)	Inside Diameter After Flow-Turning (inches)	Feed-Reduction Parameter (1) (inches/rev./roller)	Diametral Growth (2) (inches/inch)
3.5	63	0.048	9.451	0.0079	0.00148
3.5	54	0.060	9.480	0.00675	0.00392
4.5	60	0.062	9.449	0.00965	0.00074
6	43	0.074	9.413	0.0086	0.00127
4.5	69	0.057	9.425	0.01035	0.00053

peed) (per cent reduction/100)
/initial diameter

1

Flow-Turning Parameters and Di

(1

Fi

Cylinder Number	Inside Diameter Before Flow-Turning (Inches)	Wall Thickness Before Flow-Turning (Inches)	Mandrel Speed (RPM)	Roller Feed (Inches/Min/Roller)	Reduction (Per Cent)
1	14.132	0.300 - 0.301	200	4	51.8
2	14.133	0.299 - 0.301	200	4	50.0
3	14.127	0.301 - 0.302	200	4	43.7
4	14.127	0.300 - 0.301	200	3.45	48.5
5	14.127	0.300 - 0.301	200	3	54
6	14.129	0.298 - 0.302	200	3	51.3
7	14.126	0.301	200	3.0	50.1
8	14.134	0.301	200	3.85	52.9
9	14.124	0.303	150	3	55.2
10	14.125	0.303	150	3	53.5
					Secc
1	14.138	0.140 - 0.147	200	4	49.5
2	14.130	0.149 - 0.152	200	5	50
3	14.130	0.169 - 0.173	200	3.45	55.5
4	14.130	0.151 - 0.157	200	3.85	53.8
5	14.130	0.136 - 0.140	200	4	(3)
6	14.130	0.142 - 0.147	200	4	46
7	14.136	0.150	200	4	53.9
8	14.131	0.142	200	4	50.7
9	14.127	0.130	150	3.0	48.2
10	14.128	0.134	150	3.0	42.5

(1) Feed-reduction parameter equals (roller feed/mandrel speed) (per cent reduction (

(2) Diametral growth equals (final diameter-initial diameter) / initial diameter

(3) Failed during second pass due to machine malfunctions

2

TABLE XXIII

Iurning Parameters and Dimensions of Subscale 14-Inch Diameter Cylinders

(Roll-Forged Rings)

First Flow-Turn Pass

ller ed Min/Roller)	Reduction (Per Cent)	Wall Thickness After Flow-Turning (Inches)	Inside Diameter After Flow-Turning (Inches)	Feed-Reduction Parameter(1) (Inches/Rev/Roller)	Diametral Growth(2) Inches/Inch	Roller Tip Radius (Inches)
	51.8	0.140-0.147	14.138	0.01038	0.000425	0.062 Sharp
	50.0	0.149-0.152	14.160	0.0100	0.00191	0.100
	43.7	0.169-0.173	14.143	0.00874	0.00112	0.062 Sharp
.45	48.5	0.151-0.157	14.151	0.00827	0.00168	0.062 Sharp
	54	0.136-0.140	14.146	0.00810	0.00134	0.062 Sharp
	51.3	0.142-0.147	14.142	0.00770	0.00092	0.062 Sharp
.0	50.1	0.150	14.153	0.00752	0.00191	0.062 Sharp
.85	52.9	0.142	14.144	0.01019	0.000708	0.062 Sharp
	55.2	0.136	14.119	0.01103	-0.000354	0.062 Mod.
	53.5	0.140	14.150	0.01070	0.00177	0.062 Sharp

Second Flow-Turn Pass

ller ed Min/Roller)	Reduction (Per Cent)	Wall Thickness After Flow-Turning (Inches)	Inside Diameter After Flow-Turning (Inches)	Feed-Reduction Parameter(1) (Inches/Rev/Roller)	Diametral Growth(2) Inches/Inch	Roller Tip Radius (Inches)
	49.5	0.071-0.075	14.154	0.00990	0.00113	0.100
	50	0.073-0.078	14.141	0.01000	0.00078	0.062 Sharp
.45	55.5	0.075-0.077	14.149	0.00950	0.00134	0.062 Sharp
.85	53.8	0.069-0.073	14.179	0.01040	0.00347	0.220
	(3)					0.220
	46	0.069-0.081	14.176	0.00920	0.00325	0.0220
	53.9	0.069	14.132	0.01080	-0.000283	0.062 Mod.
	50.7	0.070	14.127	0.01014	-0.000283	0.062 Mod.
.0	48.2	0.067	14.130	0.00964	0.000212	0.062 Mod.
.0	42.5	0.077	14.147	0.00850	0.00134	0.062 Mod.

speed) (per cent reduction (100)
r) / initial diameter

TABLE XXIV

Tensile Properties of Full Scale 40-Inch Diameter Rolled Ring Test Material Re-Solution Treated at 1800F for Various Times and Water-Quenched

Ring Number	Re-Solution Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)	Notched Tensile Strength (K_t = 8, ksi)
3	1800F(1/4)WQ	142.0	126.0	118.0	17.0	51.5	212.0
3	1800F(1/4)WQ	141.0	126.8	119.7	17.5	51.5	--
4	1800F(1/4)WQ	141.0	127.2	122.2	17.5	51.5	210.5
4	1800F(1/4)WQ	138.6	127.3	121.3	17.0	52.0	213.5
8	1800F(1/4)WQ	141.5	132.0	125.0	17.5	51.0	210.5
8	1800F(1/4)WQ	138.0	127.8	122.6	19.5	51.5	192.0
8	1800F(1/2)WQ	139.0	127.0	118.0	17.5	52.0	200.8
8	1800F(1/2)WQ	139.8	129.2	120.6	15.5	47.5	208.5
8	1800F(1/2)WQ	137.0	127.4	120.7	18.5	55.5	206.8
8	1800F(1/2)WQ	140.0	129.0	121.8	17.5	52.0	206.5
8	1800F(1)WQ	136.0	127.0	122.3	19.5	53.5	201.5
8	1800F(1)WQ	140.8	128.8	124.2	16.5	48.0	179.5

TABLE XXV

Tensile Properties of 9.4-Inch Diameter Cylinders As-Flow-Turned and After Direct Aging at 600 to 950F

Condition	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
As-flow-turned	199.0	183.8	158.6	6.5
As-flow-turned	200.2	189.0	165.8	7.0
600F(4)AC	193.2	180.9	158.9	7.0
600F(8)AC	192.8	170.0	139.6	6.0
600F(12)AC	196.2	183.0	162.2	8.0
700F(4)AC	201.7	190.4	164.8	6.0
700F(8)AC	139.2	176.2	152.8	8.5
700F(12)AC	217.0	205.0	182.4	3.0
800F(1/2)AC	191.2	182.2	164.9	6.0
800F(1)AC	194.9	187.4	168.9	7.0
800F(2)AC	200.4	192.0	174.2	7.0
850F(1/2)AC	181.0	172.8	145.4	9.0
850F(1)AC	181.9	174.2	153.6	8.0
850F(2)AC	195.6	188.8	172.2	6.0
900F(1)AC	177.4	170.5	158.9	8.0
900F(2)AC	185.4	175.6	155.2	7.0
900F(3)AC	196.2	185.2	160.4	4.0
950F(1/2)AC	169.4	163.0	134.4	10.0
950F(1)AC	175.2	169.9	163.8	10.0
950F(4)AC	186.2	175.0	162.6	8.5

Note: All specimens circumferentially oriented.

TABLE XXVI

Tensile Properties of 9.4 - Inch Diameter Flow-Turned Cylinders After Stress-Relieving at 850 to 950F and Aging at 700 to 900F

Stress-Relief Treatment	Aging Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
850F(1/2)AC	700F(2)AC	184.0	175.4	163.6	8.0
850F(1/2)AC	700F(4)AC	188.4	179.4	156.4	8.0
850F(1/2)AC	800F(1/2)AC	181.0	175.2	154.2	8.5
850F(1/2)AC	800F(1)AC	186.6	180.2	167.4	8.0
850F(1/2)AC	800F(2)AC	190.0	181.8	151.4	7.0
850F(1)AC	800F(1/2)AC	185.9	177.9	157.4	8.0
850F(1)AC	800F(2)AC	190.2	183.9	165.2	6.0
900F(1)AC	700F(2)AC	181.2	176.2	166.4	7.0
900F(1)AC	700F(8)AC	207.4	202.8	184.0	5.0
900F(1)AC	800F(1/2)AC	180.9	170.4	152.4	10.0
900F(1)AC	800F(1)AC	178.9	172.0	146.6	8.0
900F(1)AC	800F(2)AC	186.2	181.2	176.8	9.0
950F(1/2)AC	700F(4)AC	174.9	167.2	148.4	8.0
950F(1/2)AC	700F(8)AC	175.6	168.8	154.4	9.0
950F(1/2)AC	700F(12)AC	182.8	174.2	151.2	9.0
950F(1/2)AC	800F(2)AC	177.0	166.8	144.6	9.0
950F(1/2)AC	800F(5)AC	183.2	174.0	151.2	7.0
950F(1/2)AC	800F(8)AC	188.4	176.8	152.6	6.0
950F(1)AC	800F(2)AC	182.6	174.6	162.2	7.0
950F(1)AC	800F(5)AC	183.2	171.8	152.8	7.0
950F(1)AC	800F(8)AC	191.2	174.4	144.2	7.0
950F(1)AC	800F(12)AC	198.4	188.4	170.4	7.5
850F(1/2)AC	900F(1)AC	184.7	175.3	-	6.0
850F(1/2)AC	900F(2)AC	196.4	-	-	6.0
850F(1)AC	900F(1)AC	192.9	178.5	-	6.0
850F(1)AC	900F(2)AC	199.7	185.8	-	6.0

Note: All specimens circumferentially oriented

TABLE XXVII

Smooth and Notched Tensile Properties of Subscale 14-Inch Diameter B-120 VCA Flow-Turned Cylinder Number 4 After Various Stress-Relieving and Aging Heat Treatments

Stress-Relief Treatment	Aging Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t = 8, ksi)
850F(1/2)AC	700F(11)AC	196.0	187.3	8.0	162.3
850F(1/2)AC	700F(11)AC	198.0	186.3	8.0	160.0
850F(1/2)AC	800F(2.5)AC	195.7	187.4	6.5	168.1
850F(1/2)AC	800F(2.5)AC	196.0	187.7	7.5	164.5
850F(1/2)AC	900F(1.5)AC	197.4	188.0	9.5	135.6
850F(1/2)AC	900F(1.5)AC	201.0	192.0	6.5	160.8
850F(1)AC	800F(3)AC	197.3	185.3	5.5	153.3
850F(1)AC	800F(3)AC	204.0	185.7	6.5	149.2
900F(1)AC	700F(18)AC	193.8	187.0	8.0	164.2
900F(1)AC	700F(18)AC	194.0	183.5	8.0	136.3
900F(1)AC	800F(7)AC	203.0	193.2	5.5	138.0
900F(1)AC	800F(7)AC	198.0	190.6	5.5	144.5
900F(1)AC	900F(3.5)AC	220.0	207.0	5.5	128.0
900F(1)AC	900F(3.5)AC	221.5	209.0	5.5	122.3

TABLE XXVIII

Stress-Relief Data for 9.4-Inch Diameter Flow-Turned Cylinders

Stress-Relief Treatment	Stress Remaining After Relief (psi)	Per Cent Stress-Relief
As-Flow-Turned	65,100	0
600F(4)AC	45,700	30
600F(8)AC	44,300	32
700F(2)AC	41,300	36
700F(4)AC	36,200	44
700F(8)AC	33,400	49
800F(2)AC	21,200	67
800F(4)AC	13,900	79
800F(8)AC	4,800	93
850F(1/2)AC	23,300	64
850F(1)AC	19,300	70
850F(4)AC	3,300	95
900F(1)AC	8,200	87
900F(2)AC	700	99
950F(1/2)AC	9,800	88
950F(1)AC	0	100

TABLE XXIX

Stress-Relief Data for 9.4-Inch and 40-Inch Diameter Flow-Turned Cylinders

Cylinder Diameter (Inches)	Heat Treatment	Residual Stress (psi) Before Heat Treatment	After Heat Treatment	Per Cent Stress Relief
9.4	850F(1/2)AC	65,100	22,800	65
	850F(1/2)AC+ 800F(1)AC	65,100	22,200	66
	850F(1/2)AC+ 800F(4)AC	65,100	11,400	82
40	800F(4)AC	65,100	21,400	67
	800F(8)AC	65,100	15,900	76
	850F(1/2)AC	65,100	32,400	50
	850F(1/2)AC+ 700F(8)AC	65,100	25,200	61
	850F(1/2)AC+ 800F(1)AC	65,100	28,200	57
	850F(1/2)AC+ 800F(4)AC	65,100	18,700	71

TABLE XXX

Tensile Properties of 9.4 Inch Diameter Flow-Turned Cylinders
Annealed at 1400 to 1500F and Aged at 800 to 900F.

Anneal	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
1400F(1/2)AC	800F(48)AC	137.2	135.5	124.0	20.0
"	800F(64)AC	140.2	136.2	124.0	22.0
"	800F(22)AC	143.9	138.6	127.8	16.0
"	900F(24)AC	149.0	140.8	133.2	14.0
"	900F(48)AC	173.4	159.5	146.0	12.0
"	900F(64)AC	178.0	160.8	143.0	12.0
"	900F(72)AC	197.8	180.2	156.0	9.0
1450F(1/4)AC	800F(48)AC	153.5	147.2	135.0	15.0
"	800F(64)AC	176.5	161.8	150.0	10.0
"	800F(72)AC	185.9	168.9	134.4	10.0
"	900F(24)AC	152.0	142.4	129.6	12.0
"	900F(48)AC	173.4	159.6	144.4	11.0
"	900F(64)AC	185.2	163.8	148.8	9.0
"	900F(72)AC	190.6	174.6	148.8	8.0
1500F(1/12)AC	800F(48)AC	174.4	164.5	140.4	10.0
"	800F(64)AC	189.4	174.8	153.6	9.0
"	800F(72)AC	188.9	178.2	161.4	7.0
"	900F(24)AC	174.8	158.0	145.2	12.0
"	900F(48)AC	178.4	164.2	148.2	9.0
"	900F(64)AC	192.8	178.6	161.4	8.0
"	900F(72)AC	194.4	180.8	161.0	8.0

Note: All specimens circumferentially oriented

TABLE XXXI

Axial Tensile Properties of
Subscale 14-Inch Diameter Flow-Turned Cylinders Numbers 1, 2 and 3
Stress-Relieved at 900F for One Hour and Aged at 700 to 900F

Cylinder Number	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)
1	None	178.0	168.0	8.5
1	None	179.0	169.6	10.0
1	700F(2)AC	182.0	174.0	9.0
1	700F(4)AC	181.0	171.0	9.0 (1)
1	700F(8)AC	185.0	174.0	8.0
1	800F(2)AC	178.0	177.0	2.5 (2)
1	800F(4)AC	191.0	179.0	9.0
1	800F(8)AC	200.0	183.0	9.0
1	900F(2)AC	206.0	184.0	7.0 (1)
1	900F(4)AC	218.0	183.0	7.0
1	900F(8)AC	225.0	187.0	4.0 (2)
2	None	178.0	168.0	8.0
2	None	178.0	168.0	9.0
2	700F(2)AC	180.5	170.0	8.0
2	700F(4)AC	179.3	167.3	8.0
2	700F(8)AC	181.0	169.0	9.0
2	800F(2)AC	182.6	171.[illegible]	8.0
2	800F(4)AC	188.7	179.0	7.5
2	800F(8)AC	198.0	183.4	7.0
2	900F(2)AC	203.0	184.3	7.0
2	900F(4)AC	210.9	188.5	4.0
2	900F(8)AC	219.0	186.0	2.0
3	None	184.9	173.6	8.0
3	None	184.5	176.0	8.0
3	700F(2)AC	187.8	178.2	8.0
3	700F(4)AC	190.4	183.4	8.0
3	700F(8)AC	194.4	186.0	7.0
3	800F(2)AC	196.2	185.2	7.0
3	800F(4)AC	202.0	189.4	7.0
3	800F(8)AC	216.0	204.6	5.0
3	900F(2)AC	213.8	198.4	5.0
3	900F(4)AC	225.4	206.0	3.0
3	900F(8)AC	231.0	204.0	2.0

(1) Broke on gage mark.

(2) Broke in outer 1/3 of gage length.

TABLE XXXII

Tensile Properties of Subscale 14-Inch Diameter
Flow-Turned Cylinders Numbers 1, 2, and 3 Stress-Relieved
at 900F for One Hour and Aged at 900F

Cylinder Number	Location	Direction	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t = 8, ksi)
1	Rear	Axial	900F(2)AC	201.1	186.5	7.5	146.2
1	Rear	Axial	900F(2)AC	204.7	191.8	7.5	132.7
1	Flange	Axial	900F(2)AC	202.0	186.9	8.5	148.3
1	Flange	Axial	900F(2)AC	201.0	184.7	7.5	-
1	Flange	Circ.	900F(2)AC	198.5*	182.5*	5.0*	152.4
1	Flange	Circ.	900F(2)AC	213.0	194.3	5.0	140.2
1	Rear	Circ.	900F(2)AC	213.5	196.0	5.5	158.4
1	Rear	Circ.	900F(2)AC	211.0	195.5	5.5	139.4
2	Rear	Axial	900F(2)AC	209.3	195.4	7.5	150.7
2	Rear	Axial	900F(2)AC	205.5	192.4	7.5	138.8
2	Flange	Axial	900F(2)AC	208.0	194.4	8.0	146.5
2	Flange	Axial	900F(2)AC	206.5	192.9	7.5	14[illegible].4
2	Flange	Circ.	900F(2)AC	216.7	201.0	5.0	152.8
2	Flange	Circ.	900F(2)AC	218.0	199.4	5.0	141.3
2	Rear	Circ.	900F(2)AC	216.0	200.5	5.0	126.0
2	Rear	Circ.	900F(2)AC	219.4	204.5	5.0	141.9
3	Rear	Axial	900F(1)AC	189.0	174.9	9.5	159.5
3	Rear	Axial	900F(1)AC	183.6	176.3	8.5	150.7
3	Flange	Axial	900F(1)AC	188.5	176.5	8.0	142.[illegible]
3	Flange	Axial	900F(1)AC	192.8	182.0	8.0	151.9
3	Flange	Circ.	900F(1)AC	168.0*	162.8*	2.0*	140.5
3	Flange	Circ.	900F(1)AC	208.3	194.0	5.0	142.0
3	Rear	Circ.	900F(1)AC	202.5	181.2	5.0	[illegible]
3	Rear	Circ.	900F(1)AC	202.8	184.9	2.5	146.1
3	Flange	Axial	900F(1)AC	200.0	186.5	7.0	135.5
3	Flange	Axial	900F(1)AC	203.	190.4	8.0	133.3
3	Flange	Circ.	900F(1)AC	211.0	196.4	7.0	107.5
3	Flange	Circ.	900F(1)AC	183.0*	172.0*	5.0*	132.3

* Specimen contained unflow-turned material

TABLE XXXIII

Tensile Properties of Subscale 14-inch Diameter Flow-Turned Cylinders Numbers 1, 2, and 3 After Solution Treatment at 1400F and Aging at 900F

Solution Treatment	Age	Cylinder Number	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
1400F(1/2)WQ	None	1	136.5	130.8	123.8	20.0
1400F(1/2)WQ	900F(48)AC	1	171.5	155.3	144.0	11.0
1400F(1/2)WQ	900F(72)AC	1	180.0	164.5	156.7	11.0
1400F(1/2)WQ	900F(96)AC	1	193.2	173.8	162.2	8.0
1400F(1/2)WQ	None	2	136.2	131.9	126.2	18.0
1400F(1/2)WQ	900F(43)AC	2	164.0	148.7	140.5	11.0
1400F(1/2)WQ	900F(72)AC	2	189.7	170.0	154.9	10.0
1400F(1/2)WQ	900F(96)AC	2	198.6	180.0	167.3	7.0
1400F(1/2)WQ	None	3	145.5	140.9	134.0	18.0
1400F(1/2)WQ	900F(48)AC	3	180.2	169.5	159.0	11.0
1400F(1/2)WQ	900F(72)AC	3	193.8	174.0	163.9	9.0
1400F(1/2)WQ	900F(96)AC	3	211.5	187.4	174.2	8.0

Note: All specimens axially oriented

TABLE XXXIV

Tensile Properties of Subscale 14-Inch Diameter Flow-Turned Cylinder Number 4 After Stress-Relieving at 850 to 900F and Aging at 700 to 900F

Stress-Relief	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
850F(1/2)AC	None	184.8	172.8	157.0	10.0
	700F(4)AC	196.5	185.0	173.0	6.5
	700F(8)AC	197.8	183.5	163.2	4.5
	700F(12)AC	205.5	191.8	166.4	6.5
	700F(16)AC	209.5	197.8	177.0	5.5
	800F(1)AC	194.3	181.4	164.8	5.5
	800F(2)AC	198.0	186.0	169.8	5.5
	800F(4)AC	216.0	204.5	188.4	5.5
	800F(8)AC	233.5	220.5	203.5	4.5
	900F(1)AC	193.2	181.4	171.0	8.0
	900F(2)AC	207.0	193.3	175.8	6.0
	900F(4)AC	228.0	216.0	200.0	4.0
	900F(8)AC	235.0	223.0	203.5	3.5
850F(1)AC	None	187.0	175.3	158.0	6.5
	700F(4)AC	197.5	188.5	176.3	6.5
	700F(8)AC	200.0	187.8	175.8	8.5
	700F(12)AC	207.0	191.8	180.5	6.5
	700F(16)AC	210.0	195.0	176.8	6.5
	800F(1)AC	194.2	180.5	168.0	6.5
	800F(2)AC	202.5	189.3	177.0	6.5
	800F(4)AC	201.5	190.0	173.6	5.0
	800F(8)AC	224.0	201.0	190.0	2.5
	900F(1)AC	199.0	189.2	176.0	6.5
	900F(2)AC	208.5	198.0	187.0	6.0
	900F(4)AC	226.5	213.0	193.0	4.0
	900F(8)AC	236.0	222.0	205.0	4.0
900F(1)AC	None	182.0	170.0	158.0	8.5
	700F(4)AC	183.3	173.5	163.3	8.5
	700F(8)AC	186.0	175.6	166.0	8.5
	700(12)AC	189.0	178.8	169.0	8.5
	700F(16)AC	193.8	182.2	167.0	6.0
	800F(1)AC	187.0	171.0	161.0	8.5
	800F(2)AC	189.4	176.0	167.4	8.5
	800F(4)AC	198.8	183.2	171.3	4.5
	800F(8)AC	206.5	190.8	177.4	6.5
	900F(1)AC	194.8	180.5	169.7	6.5
	900F(2)AC	201.5	187.4	177.3	5.0
	900F(4)AC	203.0	189.3	176.0	6.5
	900F(8)AC	218.0	198.5	181.8	6.0

Note: All specimens axially oriented

TABLE XXXV

Tensile Properties of Subscale 14-Inch Diameter Flow-Turned Cylinder Number 4 After Aging at 900F

Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t = 8, ksi)
900F(3)AC	215.0	198.0	181.0	4.0	137.5
900F(3)AC	204.0	194.0	176.1	4.0	135.8
900F(5)AC	222.0	210.0	142.7	4.5	131.8
900F(5)AC	228.0	214.0	146.5	5.0	118.4

Note: All specimens circumferentially oriented

TABLE XXXVI

Smooth and Notched Tensile Properties of Subscale 14-Inch Diameter B-120 VCA Titanium Alloy Flow-Turned Cylinder Number 4

Stress-Relief	Age	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t =8, ksi)
850F(1/2)AC	700F(11)AC	196.0	187.3	8.0	162.3
850F(1/2)AC	700F(11)AC	198.0	186.3	8.0	160.0
850F(1/2)AC	800F(2.5)AC	195.7	187.4	6.5	168.1
850F(1/2)AC	800F(2.5)AC	196.0	187.7	7.5	164.5
850F(1/2)AC	900F(1.5)AC	197.4	188.0	9.5	135.6
850F(1/2)AC	900F(1.5)AC	201.0	192.0	6.5	160.8
850F(1)AC	800F(3)AC	197.3	185.3	5.5	153.3
850F(1)AC	800F(3)AC	204.0	185.7	6.5	149.2
900F(1)AC	700F(18)AC	193.8	187.0	8.0	164.2
900F(1)AC	700F(18)AC	194.0	183.5	8.0	136.3
900F(1)AC	800F(7)AC	203.0	193.2	5.5	138.0
900F(1)AC	800F(7)AC	198.0	190.6	5.5	144.5
900F(1)AC	900F(3.5)AC	220.0	207.0	5.5	128.0
900F(1)AC	900F(3.5)AC	221.5	209.0	5.5	122.3

Note: All specimens circumferentially oriented

TABLE XXXVII

Tensile Properties of Subscale 14-Inch Diameter
Cylinder Number 7 Solution-Treated at 1800F Prior to Flow-Turning

Stress-Relief Treatment	Aging Treatment	Specimen Direction	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)
850F (1/2)AC	None	Axial	187.5	181.0	4.0
"	"	"	188.3	181.0	4.5
"	"	Circum.	197.8	188.0	6.5
"	"	"	196.0	187.0	5.5
"	800F(1)AC	Axial	201.5	193.3	3.5
"	"	"	205.5	197.0	2.0
"	"	Circum.	216.5	206.0	5.0
"	"	"	215.0	206.5	4.0
"	800F(2)AC	Axial	210.5	200.0	3.0
"	"	"	218.5	208.5	2.5
"	"	Circum.	222.5	213.0	3.0
"	"	"	222.5	212.5	3.0
"	800F(4)AC	Axial	216.0	208.5	2.0
"	"	"	231.5	224.0	2.0
"	"	Circum.	235.5	226.0	2.5
"	"	"	236.0	225.5	3.0
"	800F(8)AC	Axial	227.0	223.5	1.0
"	"	"	218.0	-	1.0
"	"	Circum.	245.5	236.5	2.5
"	"	"	248.5	238.5	2.5

TABLE XXXVIII

Tensile Properties of 14-Inch Diameter Cylinder
Number 8 Flow-Turned by the Present Two-Pass Technique
(50% Reduction Per Pass), Stress Relieved
at 850F for One-Half Hour, and Aged at 800F

Condition	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -(1" Gauge) (Per Cent)
As-stress-relieved	186.6	173.0	4.0
As-stress-relieved	193.2	185.0	4.0
800F (1/2) AC	190.0	182.8	6.5
800F (1/2) AC	189.4	182.6	2.0
800F (1) AC	198.5	190.2	3.5
800F (1) AC	198.0	191.3	6.5
800F (2) AC	211.5	203.0	4.5
800F (2) AC	146 *		
800F (4) AC	220.0	211.0	2.0
800F (4) AC	221.5	212.0	2.0

*Specimen Failed Through Prior Crack

TABLE XXXIX

Axial Tensile Properties of Subscale 14-Inch Diameter Cylinder Number 9 Flow-Turned by the Present Two-Pass Technique (50 Per Cent Reduction Per Pass), Stress-Relieved at 850F for One-Half Hour and Aged at 800F

Condition	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t=8) (ksi)
As-stress-relieved	193.0	186.4	4.5	153.5
As-stress-relieved	200.2	191.0	5.0	147.5
800F(1/2)AC	205.0	193.6	5.0	
800F(1/2)AC	206.5	198.0	5.0	
800F(1)AC	208.5	196.5	5.0	138.0
800F(1)AC	215.5	204.5	3.0	149.6
800F(2)AC	218.0	209.0	5.0	
800F(2)AC	216.0	206.0	3.0	
800F(4)AC	231.5	210.0	3.0	
800F(4)AC	226.5	215.0	4.0	
800F(3)AC				128.4
300F(3)AC				137.8

TABLE XL

Tensile Properties of 14-Inch Diameter Cylinder Number 10 Flow-Turned by the Present Two-Pass Technique (50 Per Cent Reduction Per Pass), Stress-Relieved at 850F for One-Half Hour and Aged at 800F

Condition	Specimen Direction	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t=8) (ksi)
As-stress-relieved	Axial	179.9	172.7	9.0	
As-stress-relieved	Axial	180.5	173.0	7.5	
As-stress-relieved	Circ.	188.3	175.6	9.0	
800F(1/2)AC	Axial	185.8	178.3	8.0	
800F(1/2)AC	Axial	186.2	175.5	7.0	
800F(1/2)AC	Circ.	194.0	182.8	7.0	
800F(1/2)AC	Circ.	195.3	184.0	7.0	
800F(1)AC	Axial	188.0	[illegible]	7.0	151.5
800F(1)AC	Axial	188.8	180.7	7.0	160.0
800F(1)AC	Circ.	204.5	192.3	6.0	169.0
800F(1)AC	Circ.	199.0	186.0	6.0	171.0
800F(2)AC	Axial	195.6	187.9	7.0	
800F(2)AC	Axial	198.7	189.5	6.0	
800F(2)AC	Circ.	206.0	190.5	6.0	
800F(2)AC	Circ.	205.0	191.4	6.0	
800F(4)AC	Axial	208.0	197.8	5.0	128.5
800F(4)AC	Axial	206.2	196.5	5.0	127.6
800F(4)AC	Circ.	217.5	207.0	5.0	146.8
800F(4)AC	Circ.	217.0	203.0	4.5	138.5
800F(8)AC	Circ.	227.0	216.0	3.0	121.0
800F(8)AC	Circ.	228.0	216.0	3.0	119.5
800F(8)AC	Axial				120.0
800F(8)AC	Axial				115.5

TABLE XLI

Fracture Toughness Of 0.075-Inch Thick Flow-Turned
And Aged B-120 VCA Titanium Alloy 14-Inch Diameter Cylinders
Numbers 10 and 9

Cylinder	Direction	Yield Strength Level (ksi)	Fracture Toughness G_c* (in-lbs/in^2)	Net Section Stress (ksi)
10	Axial	180	540	101
	Axial	180	558	103
	Circ.	188	448	110
	Circ.	188	448	92
	Circ.	205	147	54.5
	Circ.	205	160	55
	Circ.	216	91	42
9	Axial	189	298	75
	Axial	189	342	81
	Axial	200	197	61
	Axial	200	168	57
	Axial	210	67	36

TABLE XLII

Tensile Properties of B-120 VCA Titanium Alloy
0.005-Inch Thick Sheet Stock Cold Rolled 50% and Aged

Heat Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
As-rolled	196.8	182.0	141.0	6.0
As-rolled	196.2	187.4	169.0	6.0
800F(1)AC	196.2	188.5	180.5	9.0
800F(1)AC	199.4	193.0	182.7	9.0
800F(2)AC	211.0	208.2	193.4	6.0
800F(2)AC	211.2	202.0	190.5	6.0
800F(3)AC	225.2	209.3	199.5	7.0
800F(3)AC	216.2	209.0	202.0	6.0
800F(4)AC	222.0	212.0	199.4	5.5
800F(4)AC	221.4	212.0	201.4	5.0
850F(1/2)AC	187.3	183.4	175.6	7.5
850F(1/2)AC	187.4	179.6	170.2	7.5
850F(1)AC	196.4	184.2	166.6	7.0
850F(1)AC	194.8	185.0	172.8	7.0
900F(1)AC	194.8	182.0	169.0	6.0
900F(1)AC	195.2	176.4	171.2	8.0
900F(2)AC	211.4	197.6	172.4	6.5
900F(2)AC	209.6	196.8	182.5	6.0

Note: Hydrogen content = 70 ppm

TABLE XLIII

Tensile Properties of Cold-Rolled* (50% Reduction) and Aged
(850 F (1) AC) Sheet Stock with 70 and 200 ppm Hydrogen

Hydrogen Content (ppm)	Test Temp. (°F)	Tensile Strength(ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation-1" (Per Cent)	Notched Tensile Strength (K_t=8, ksi)
70	-35	216.8	210.2	191.8	6.0	146.4
70	-35	214.2	206.8	176.6	6.0	152.0
70	-35	212.0	205.0	186.4	8.0	159.4
200	-35	213.0	203.0	177.8	6.0	159.0
200	-35	213.8	205.0	187.4	6.5	168.8
200	-35	214.4	208.0	195.0	8.5	156.4
70	70	195.0	187.6	181.0	7.0	166.8
70	70	195.0	189.5	181.6	6.5	161.6
200	70	191.6	184.0	172.5	7.0	161.0
200	70	193.0	184.5	173.4	8.0	156.0
70	200	181.0	169.5	152.6	7.0	175.5
70	200	183.8	171.8	158.6	7.0	182.4
200	200	181.4	169.4	153.8	9.0	176.8
200	200	184.6	170.4	153.8	9.0	167.0
200	200	179.0	168.5	158.0	7.5	170.8
200	200	181.8	170.4	154.8	7.5	177.4
70	400	176.4	161.8	145.0	7.0	153.4
70	400	182.0	165.8	153.0	7.0	162.8
70	400	178.0	165.4	150.6	5.0	175.5
200	400	176.2	162.2	142.0	8.0	165.8
200	400	177.2	161.4	145.6	8.0	165.8
200	400	176.0	161.5	147.2	7.0	165.8

*Specimen Axis Parallel to Rolling Direction

TABLE XLIV

Notched (K_t=8) Sustained-Load Test Results on Cold-Rolled (50% Reduction) and Aged (850 F (1) AC) Sheet Stock with 70 ppm and 200 ppm of Hydrogen

Specimen Number	Test Temperature (°F)	Hydrogen Content (ppm)	Stress (ksi)	Time at Load (Hours)	Remarks
1	-35	70	125.0	5.0	Load increased to 130.0 ksi
1	-35	70	130.0	167.4	Discontinued
2	-35	70	130.0	150.0	Discontinued
3	-35	70	140.0	0.0	Failed on loading
4	-35	200	140.0	5.0	Failed on loading to 150.0 ksi
5	-35	200	145.0	150.0	Discontinued
6	-35	200	145.0	150.0	Discontinued
7	70	70	150.0	0.0	Failed on loading
8	70	70	150.0	0.0	Failed on loading
9	70	70	145.0	150.0	Discontinued
10	[illegible]	70	150.0	150.0	Discontinued
11	70	200	150.0	5.0	Load increased to 160.0 ksi
11	70	200	160.0	0.1	Failed after 0.1 hours
12	70	200	152.5	150.0	Discontinued
13	70	200	155.0	0.0	Failed on loading
14	70	200	155.0	152.1	Discontinued
15	200	70	165.0	0.0	Failed on loading
16	200	70	155.0	4.9	Load increased to 160.0 ksi
16	200	70	160.0	157.2	Discontinued
17	200	70	160.0	150.0	Discontinued
18	200	200	165.0	5.0	Load increased to 170.0 ksi
18	200	200	170.0	0.0	Failed on loading
19	200	200	165.0	152.6	Discontinued
20	200	200	165.0	150.0	Discontinued
21	400	70	155.0	5.6	Load increased to 160.0 ksi
21	400	70	160.0	5.4	Load increased to 165.0 ksi
21	400	70	165.0	9.6	Failed after 9.6 hours
22	400	70	160.0	0.0	Failed on loading
[illegible]	400	70	155.0	150.0	Discontinued
24	400	70	155.0	150.0	Discontinued
25	400	200	160.0	0.0	Failed on loading
26	400	200	155.0	150.3	Discontinued
27	400	200	155.0	150.0	Discontinued

TABLE XLV

Notched (K_t = 3) Sustained-Load Test Results on Cold-Rolled (50% Reduction) and Aged (850 F (1) AC) Sheet Stock with 70 ppm and 200 ppm of Hydrogen

Specimen Number	Hydrogen Content	Stress (ksi)	Time at Load(Hours)	Remarks
1	70	145.0	5.0	Load increased to 150.0 ksi
1	70	150.0	5.0	Load increased to 155.0 ksi
1	70	155.0	5.0	Load increased to 160.0 ksi
1	70	160.0	5.0	Load increased to 165.0 ksi
1	70	165.0	5.0	Load increased to 190.0 ksi
1	70	190.0	5.0	Load increased to 195.0 ksi
1	70	195.0	5.0	Load increased to 200.0 ksi
1	70	200.0	0.4	Failed after 0.4 hours
2	70	195.0	150.0	Discontinued
3	200	145.0	5.0	Load increased to 150.0 ksi
3	200	150.0	5.0	Load increased to 155.0 ksi
3	200	155.0	5.0	Load increased to 160.0 ksi
3	200	160.0	5.0	Load increased to 165.0 ksi
3	200	165.0	5.0	Load increased to 190.0 ksi
3	200	190.0	5.0	Load increased to 195.0 ksi
3	200	195.0	5.0	Load increased to 200.0 ksi
3	200	200.0	0.0	Failed on loading
4	200	195.0	150.0	Discontinued

TABLE XLVI

Notched (K_t = 6) Sustained-Load Test Results
on Cold-Rolled (50% Reduction) and
Aged (850 F (1) AC) Sheet Stock with
70 ppm and 200 ppm of Hydrogen

Specimen Number	Hydrogen Content	Stress (ksi)	Time at Load (Hours)	Remarks
1	70	145.0	5.0	Load increased to 150.0 ksi
1	70	150.0	5.0	Load increased to 155.0 ksi
1	70	155.0	5.0	Load increased to 160.0 ksi
1	70	160.0	0.3	Failed after 0.3 hours
2	70	155.0	150.0	Discontinued
3	200	145.0	5.0	Load increased to 150.0 ksi
3	200	150.0	5.0	Load increased to 155.0 ksi
3	200	155.0	5.0	Load increased to 160.0 ksi
3	200	160.0	5.0	Load increased to 165.0 ksi
3	200	165.0	5.0	Load increased to 170.0 ksi
3	200	170.0	0.1	Failed after 0.1 hours
4	200	165.0	0.0	Failed on loading
5	200	160.0	0.0	Failed on loading
6	200	155.0	150.0	Discontinued

TABLE XLVII

Axial Tensile Properties of Subscale 14-Inch Diameter Cylinder Vacuum-Annealed at 1400F and Flow-Turned by the Present Two-Pass Technique (50% Reduction Per Pass)

Heat Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
850F (1/2) AC	198.0	190.5	165.0	5.0
"	194.0	184.7	156.0	5.0
850F (1/2) AC + 900F (1/2) AC	199.3	188.6	170.0	6.0
"	198.5	189.3	175.3	2.5
850F (1/2) AC + 900 (1) AC	198.0	-	180.5	1.0
"	217.0	208.0	190.2	1.0
850F (1/2) AC + 900F (2) AC	207.5	-	198.3	1.0
"	124.2	-	-	0.5
850F (1/2) AC + 900 (4) AC	209.5	-	192.3	1.0
"	224.0	220.0	198.5	1.5

TABLE XLVIII

Axial Tensile Properties of Subscale 14-Inch Diameter Cylinder Vacuum-Annealed at 1400F and Re-Solution-Treated at 1800F (15 minutes) Prior to Flow-Turning

Heat Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
850F(1/2)AC	190.9	187.0	178.6	5.0
"	188.0	180.8	170.1	6.0
850F(1/2)AC+800F(1)AC	205.0	198.2	186.5	5.0
"	204.0	196.5	189.1	3.5
850F(1/2)AC+800F(2)AC	209.0	201.0	178.5	3.0
"	207.0	199.2	187.5	4.0
850F(1/2)AC+800F(4)AC	214.0	206.0	195.6	3.0
"	215.0	208.5	198.3	3.5
850F(1/2)AC+800F(8)AC	231.5	222.5	209.0	2.0
"	202.0	192.0	180.5	3.5

TABLE XLIX

Smooth and Notched Tensile Properties of Flow-Turned (50% Reduction) and Aged (850F (1/2) AC) 14-Inch Diameter Cylinder with Hydrogen Contents of 70 and 200 ppm

Specimen Direction	Hydrogen Content (ppm)	Test Temp °F	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Notched Tensile Strength (K_t=8) (ksi)
Axial	70	70	189.3	184.8	5.0	181.0
Axial	70	70	189.1	---	4.5	170.6
Axial	200	70	186.3	173.1	5.0	180.0
Axial	200	70	189.5	186.0	4.0	156.5
Circ.	70	70	195.6	183.5	7.0	141.8
Circ.	70	70	195.1	185.6	6.5	151.0
Circ.	200	70	192.5	186.4	6.5	170.2
Circ.	200	70	194.5	186.5	7.0	157.0
Circ.	70	-40	215.0	199.0	5.0	165.0
Circ.	70	-40	216.0	202.0	5.0	162.0
Circ.	200	-40	216.5	200.0	5.0	165.6
Circ.	200	-40	208.0	194.0	2.0	168.5
Circ.	70	400	184.5	170.5	5.0	170.0
Circ.	70	400	183.5	169.0	5.0	159.8
Circ.	200	400	187.0	170.0	7.0	173.5
Circ.	200	400	185.5	170.0	4.0	160.0

TABLE L

Results of Bump-Up Tests (5 ksi Stress Increase Every 5 Hours) Conducted on Notched (K_t=8) Tensile Specimens From Flow-Turned and Aged (850F(1/2)AC) 14-Inch Diameter Cylinder

Direction	Test Temp. (°F)	Hydrogen Content (ppm)	Initial Stress (ksi)	Failure Stress (ksi)	Remarks
Axial	70	70	145	170	1 min at 170 ksi
Axial	70	200	145	160	Ruptured on increasing load to 165 ksi
Circ.	70	70	130	130	Failed on loading
Circ.	70	200	130	145	Failed after 0.1 hour
Circ.	400	70	150	165	Failed after 1.0 min.
Circ.	400	200	150	150	Failed after 1.0 min.
Circ.	-40	70	145	150	Failed after 1.4 hours at 150 ksi
Circ.	-40	200	145	-	Failed on Loading to 150 ksi

TABLE LI

Results of Sustained Load Tests Conducted on Notched Tensile Specimens From Flow-Turned and Aged (850(1/2)AC) 14-Inch Diameter Cylinder

Direction	Test Temperature (°F)	Hydrogen Content (ppm)	Stress (ksi)	Time at Stress (Hours)	Remarks	Notched (K_t=8) Strength at 70F Subsequent to Sustained Load Testing (ksi)
Circumferential	70	70	140	163	Test discontinued	167.0
Circumferential	70	200	140	165	Test discontinued	171.0
Axial	70	70	160	150	Test discontinued	173.0
Axial	70	200	160	150	Test discontinued	172.0
Circumferential	-40	70	145	161	Test discontinued	175.5
Circumferential	-40	200	145	-	Failed during loading	
Circumferential	-40	200	145	-	Failed during loading	
Circumferential	-40	200	140	150	Test discontinued	157.0
Circumferential	400	70	150	165	Test discontinued	163.0
Circumferential	400	200	145	183	Test discontinued	145.0

TABLE LII

Flow-Turning Parameters and Dimensions of Full Scale 40-Inch Diameter Cylinders

Cylinder Number	Inside Diameter Before Flow-Turning (Inches)	Wall Thickness Before Flow-Turning (Inches)	Mandrel Speed (RPM)	Roller Feed (Inches/Min/Roller)	Reduction (Per Cent)	Wall Thickness After Flow-Turning (Inches)	Inside Diameter After Flow-Turning (Inches)	Feed-Reduction Parameter(1) (Inches/Rev/Roller)	Diametral Growth(2) (Inches/Inch)	Roller Tip Radius (Inch)
First Flow-Turn Pass										
1A	39.625	0.300	52.5	1.05	31	0.207	39.680	0.0062	0.00139	0.062 Sharp
1B	39.680	0.207	52.5	1.05	26.4	0.152	39.755	0.0058	0.00189	0.062 Sharp
2	39.630	0.300	52.5	1.65(3)	46	0.162	39.637	0.0145	0.000177	0.062 Sharp
3	39.622	0.302	52.5	1.05	53.5	0.140	39.555	0.0107	-0.00169	0.062 Sharp
4	39.623	0.301	52.5	1.05	45.7	0.163	39.648	0.00914	0.00063	0.062 Sharp
5	39.621	0.300	52.5	1.05	49.3	0.152	39.616	0.06983	-0.000126	0.062 Sharp
6	39.635	0.300	52.5	1.05	48.0	0.156	39.646	0.00960	0.00053	0.062 Sharp
7	39.623	0.301	52.5	1.10	47.0	0.160	39.600	0.00985	-0.00053	0.062 Sharp
Second Flow-Turn Pass										
1	(4)									
2 (F-4)	39.622	0.152	55	1.0	52.3	0.071	39.645	0.0097	0.00058	0.062 Mod.
3	39.644	0.131	55	1.0	46.2	0.070	39.653	0.0084	0.00023	0.062 Mod.
4 (F-7)	39.654	0.1[illegible]	55	1.0	53.5	0.073	39.658	0.00972	0.00010	0.062 Mod.
5	39.622	0.146	55	1.0	53.4	0.069	39.652	0.00972	0.00076	0.062 Mod.
6 (F-2)	39.652	0.150	55	1.0	52.5	0.071	39.661	0.00955	0.00023	0.062 Mod.
7	(4)									

(1) Feed-reduction parameter equals (roller feed/mandrel speed) (percent reduction/100)
(2) Diametral growth equals ((final diameter - initial diameter)/initial diameter
(3) Estimated
(4) Cut into hoops after first pass

TABLE LIII

Effect of Aging at 800F on Tensile Properties of Specimens From Full Scale 40-Inch Diameter Ring F-4 Re-Solution Treated at 1800F, Flow-Turned by the Present Two-Pass Technique and Stress-Relieved at 850F for One-Half Hour

Heat Treatment	Direction	Specimen Gage Length (Inch)	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation-1" (Per Cent)
As stress relieved	Axial	0.75	187.0	183.0	171.0	8.0
As stress relieved	Axial	0.75	183.8	179.5	166.7	7.3
As stress relieved	Circ.	1.0	198.5	186.0	159.5	6.0
As stress relieved	Circ.	1.0	197.5	185.5	157.0	6.5
As stress relieved	Circ.	0.75	199.5	187.0	161.7	4.0
As stress relieved	Circ.	0.75	200.0	190.8	168.3	4.7
800F (1/2) AC	Axial	0.75	196.0	187.5	173.5	6.7
800F (1/2) AC	Axial	0.75	196.5	188.0	174.0	7.3
800F (1/2) AC	Circ.	1.0	207.0	197.0	174.0	6.0
800F (1/2) AC	Circ.	1.0	206.5	197.2	174.8	5.0
800F (1) AC	Axial	0.75	199.0	188.5	172.5	4.0
800F (1) AC	Axial	0.75	199.0	190.0	171.0	6.7
800F (1) AC	Circ.	1.0	208.0	198.0	176.0	4.0
800F (1) AC	Circ.	1.0	209.0	198.0	172.3	4.5
800F (2) AC	Axial	0.75	204.5	195.8	181.8	5.3
800F (2) AC	Axial	0.75	204.0	196.0	179.8	5.3
800F (2) AC	Circ.	1.0	214.5	203.5	178.0	3.0
800F (2) AC	Circ.	1.0	215.0	194.7	171.5	3.5
800F (4) AC	Axial	0.75	214.0	204.5	185.5	4.0
800F (4) AC	Axial	0.75	207.0	196.0	178.0	3.3
800F (4) AC	Circ.	1.0	228.0	216.0	196.6	3.0
800F (4) AC	Circ.	1.0	231.5	220.0	198.4	4.0

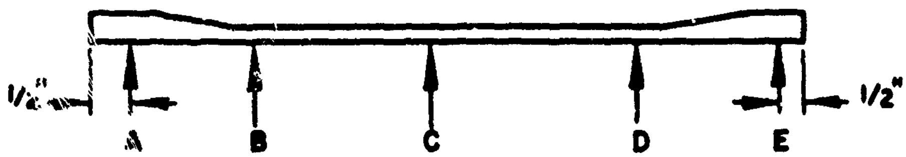
TABLE LIV

Tensile Properties of 40-Inch Diameter Roll-Forged Rings Solution Treated at 1800F for Fifteen Minutes and Water Quenched

Ring Number	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation -1" (Per Cent)	Reduction in Area (Per Cent)	Notched Tensile Strength (K_t=8) (ksi)
2	134.8	125.7	25	59	211.0
2	138.3	126.9	20	54	212.0
3	137.2	126.5	19.5	50.5	209.0
3	138.0	127.3	21.5	49	217.2
6	136.3	---	21.5	49	211.5
6	136.3	127.0	24.0	59	218.8
7	136.5	125.6	20	57.5	216.0
7	146.3	---	18.5	57.5	216.0
8	139.0	---	21.0	59.5	216.0
8	143.5	129.5	18.5	51.0	211.5

TABLE LV

**Summary of Inspection Results of
40-Inch Diameter Cylinders
After Flow-Turning**



Average Inside Diameters

Cylinder Number	A	B	C	D	E
2	39.685	39.700	39.600	39.635	39.688
3	39.600	39.655	39.663	39.643	39.652
4	39.727	39.649	39.668	39.658	39.714
5	39.724	39.644	39.658	39.654	39.733
6	39.698	39.674	39.641	39.668	39.692

Average Wall Thickness

Cylinder Number	A	B	C	D	E
2	1.147	0.070	0.071	0.073	0.146
3	0.133	0.070	0.070	0.071	0.133
4	0.144	0.070	0.073	0.075	0.145
5	0.144	0.068	0.068	0.069	0.145
6	0.143	0.072	0.071	0.071	0.146

TABLE LVI

Circumferential Tensile Properties of Full-Scale 40-Inch Diameter Cylinder F-7 Flow-Turned by the Present Two-Pass Technique (50% Reduction Each Pass) Stress-Relieved at 850F for One-Half Hour And Aged At 800-850F

Condition	Aging Heat Treatment	Ultimate Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation-1" (Per Cent)
As Received	None	194.0	187.0	164.0	6.0
As Received	None	193.5	188.0	167.0	7.0
Prestrained 0.35%	None	198.0	195.0	189.0	5.0
Prestrained 0.35%	None	202.0	199.0	198.0	6.0
Prestrained 0.35%	800F(1/2) AC	210.0	204.0	198.0	5.0
Prestrained 0.35%	800F(1/2) AC	210.0	208.0	206.0	5.0
Prestrained 0.35%	800F(1) AC	216.0	210.0	204.0	5.0
Prestrained 0.35%	800F(1) AC	221.0	216.0	208.0	4.0
Prestrained 0.35%	800F(2) AC	224.0	219.0	211.0	4.0
Prestrained 0.35%	800F(2) AC	224.0	216.0	209.0	4.0
Prestrained 0.35%	850F(1/2) AC	212.0	207.0	197.0	5.0
Prestrained 0.35%	850F(1/2) AC	213.0	207.0	197.0	5.0
Prestrained 0.35%	850F(1/2)AC*	210.0	204.0	196.5	4.0
Prestrained 0.35%	850F(1/2)AC*	210.5	207.0	191.5	4.0
As-Received	850F(1/2)AC**	195.0	191.0	179.0	4.0
As-Received	850F(1/2)AC**	195.5	191.5	178.0	3.0

* Circumferential Specimens Heat Treated with Part
** Axial Specimens Heat Treated with Part

TABLE LVII

850F Aging Response of 40-Inch Diameter Flow-Turned Cylinder F-2

Aging Heat Treatment	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation-1" Per Cent
850F (1/2) AC	210.0	202.0	190.0	4.0
850F (1/2) AC	209.0	200.0	190.0	4.0
850F (1) AC	216.0	206.0	194.0	4.0
850F (1) AC	217.5	208.0	196.5	4.0
850F (2) AC	226.0	215.0	198.0	4.0
850F (2) AC	238.0	225.0	212.0	4.0
850F(3/4)AC*	211.5	201.5	189.0	4.0
850F(3/4)AC*	211.0	201.5	192.5	4.0
850F(3/4)AC**	195.5	186.0	168.0	5.3
850F(3/4)AC**	197.5	186.5	171.0	6.7

* Circumferential Specimens Prestrained 0.4% and Heat Treated with Part
** Axial Specimens (not Prestrained) Heat Treated with Part

TABLE LVIII

Tensile Properties of Specimens From Flow-Turned Cylinder
Burst-Test Component F-4 Which Failed at 540 psig Oil Pressure

Location	Direction	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation-1" (Per Cent)
Top	Circ.	187.0*	179.0	166.0	6.0
Top	Circ.	198.0	192.0	179.0	6.0
Center	Circ.	201.0	198.5	182.0	4.0
Center	Circ.	201.5	201.5	191.0	5.0
Center	Axial	189.0	182.0	157.0	4.0
Center	Axial	187.0	178.0	153.0	7.0
Bottom	Circ.	201.0	190.0	177.0	6.0
Bottom	Circ.	191.0*	180.0	151.0	7.0

*Specimen Contained Unflow-Turned Material

TABLE LIX

Tensile Properties Of Flow-Turned Burst-Test Component F-7 Which Failed At 830 Psig Internal Oil Pressure

Specimen Location	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation - 1" (Per Cent)
Cyl. - Top - Axial	195.0	183.4	167.7	5.0
Cyl. - Top - Axial	196.0	183.5	162.8	4.0
Cyl. - Top - Circ.	210.3	199.0	167.0	4.0
Cyl. - Top - Circ.	209.5	200.6	172.8	5.0
Cyl. - Center - Axial	192.8	180.0	153.0	5.0
Cyl. - Center - Axial	192.3	177.2	150.4	4.0
Cyl. - Center - Circ.	207.0	196.8	164.0	4.5
Cyl. - Center - Circ.	207.8	197.8	161.0	4.5
Cyl. - Bottom - Axial	192.2	183.3	164.2	4.5
Cyl. - Bottom - Axial	190.7	180.0	164.0	5.0
Cyl. - Bottom - Circ.	204.8	194.0	165.0	4.0
Cyl. - Bottom - Circ.	204.0	195.3	173.5	5.0
Cyl. - Top - Axial*	198.0	188.2	167.2	4.0
Cyl. - Top - Axial*	199.2	187.9	166.8	5.0
Cyl. - Top - Circ.*	213.2	202.3	165.0	5.0
Cyl. - Top - Circ.*	213.0	204.0	181.7	5.0
Cyl. - Center - Axial*	197.0	185.0	165.8	5.0
Cyl. - Center - Axial*	196.3	179.0	161.0	5.0
Cyl. - Center - Circ.*	212.2	204.6	178.3	4.5
Cyl. - Center - Circ.*	212.2	203.0	178.0	4.5
Cyl. - Bottom - Axial*	194.2	182.8	[illegible]	5.0
Cyl. - Bottom - Axial*	194.0	182.9	159.4	4.5
Cyl. - Bottom - Circ.*	207.4	200.0	180.0	3.0
Cyl. - Bottom - Circ.*	206.8	198.3	176.2	4.5
Cyl. - Center - Axial*	141	(Notched K_t=8 Specimen)		
Cyl. - Center - Axial*	142.8	(Notched K_t=8 Specimen)		
Cyl. - Center - Circ.*	143.3	(Notched K_t=8 Specimen)		
Cyl. - Center - Circ.*	147.2	(Notched K_t=8 Specimen)		

*Specimens Located 180° on Circumference Away From Previous Specimens

TABLE LX

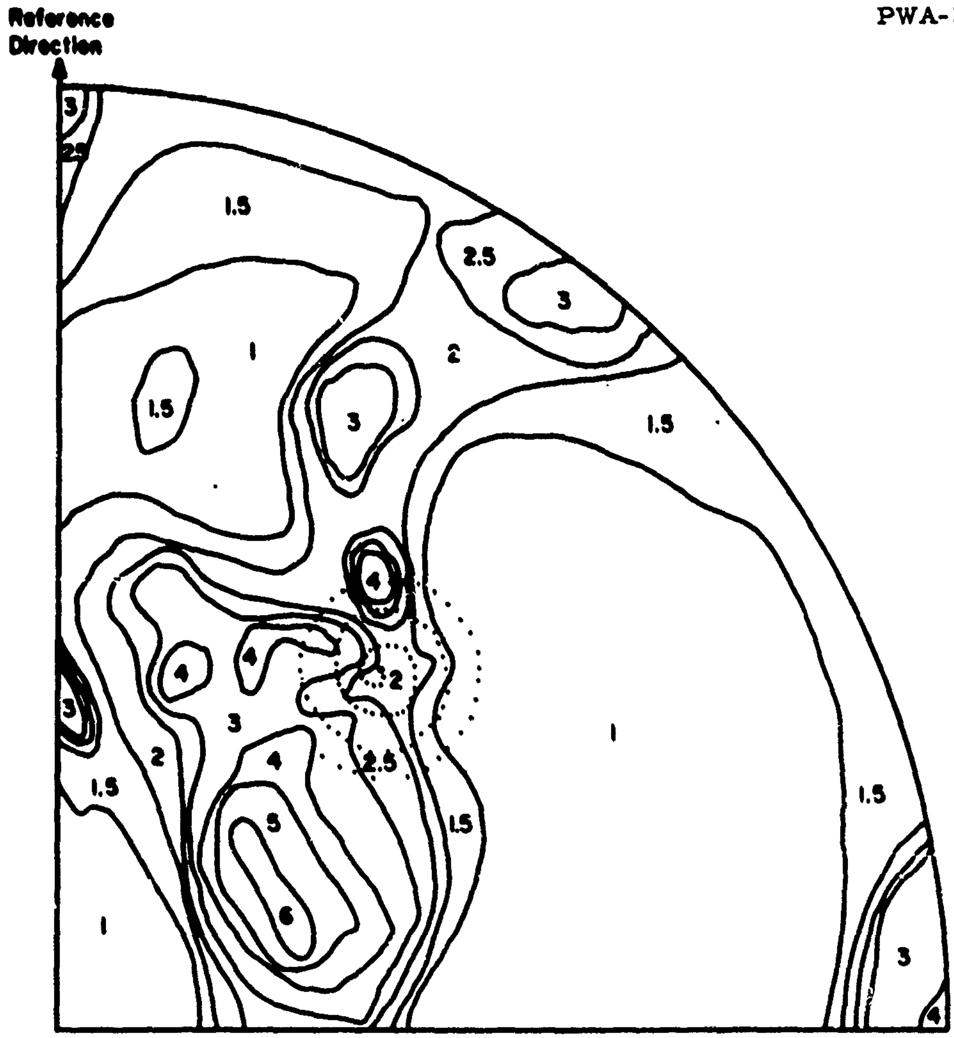
Tensile Properties of Flow-Turned Cylindrical Section F-2 From Full Scale Motor Case After Hydrostatic Burst Testing

Axial Location	Direction	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	0.02% Yield Strength (ksi)	Elongation -1" (Per Cent)
Front Closure End	Axial	208.0	197.0	171.0	3.0
	Axial	210.0	199.0	169.0	5.0
	Circumferential	225.0	216.0	192.0	4.0
	Circumferential	221.5	212.0	180.0	4.0
Center	Axial	208.0	193.0	172.0	4.0
	Circumferential	224.0	212.0	172.0	4.0
	Circumferential	225.0	216.0	186.0	4.0
Rear Closure End	Axial	208.0	197.2	176.5	4.0
	Axial	210.0	198.5	174.0	3.0
	Circumferential	212.0	202.0	170.0	4.0
	Circumferential	212.0	200.0	168.0	4.0
Test Section *	Axial	195.5	186.0	168.0	5.5
	Axial	197.5	186.5	171.0	6.5
	Circumferential	211.5	201.5	189.0	4.0
	Circumferential	211.0	201.5	192.5	4.0

* Specimens Heat Treated with the part, 850F(3/4)AC. After 0.40 per cent Prestrain to Simulate Sizing.

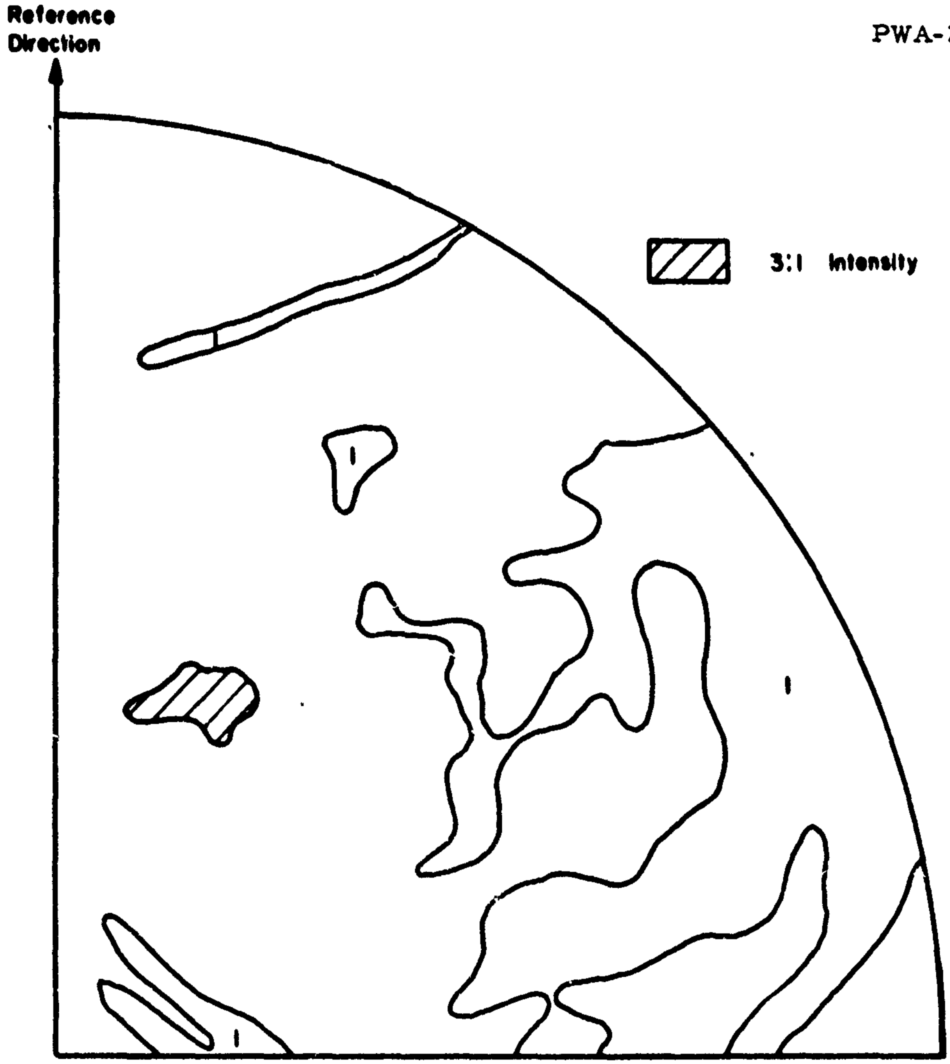
APPENDIX B

Figures



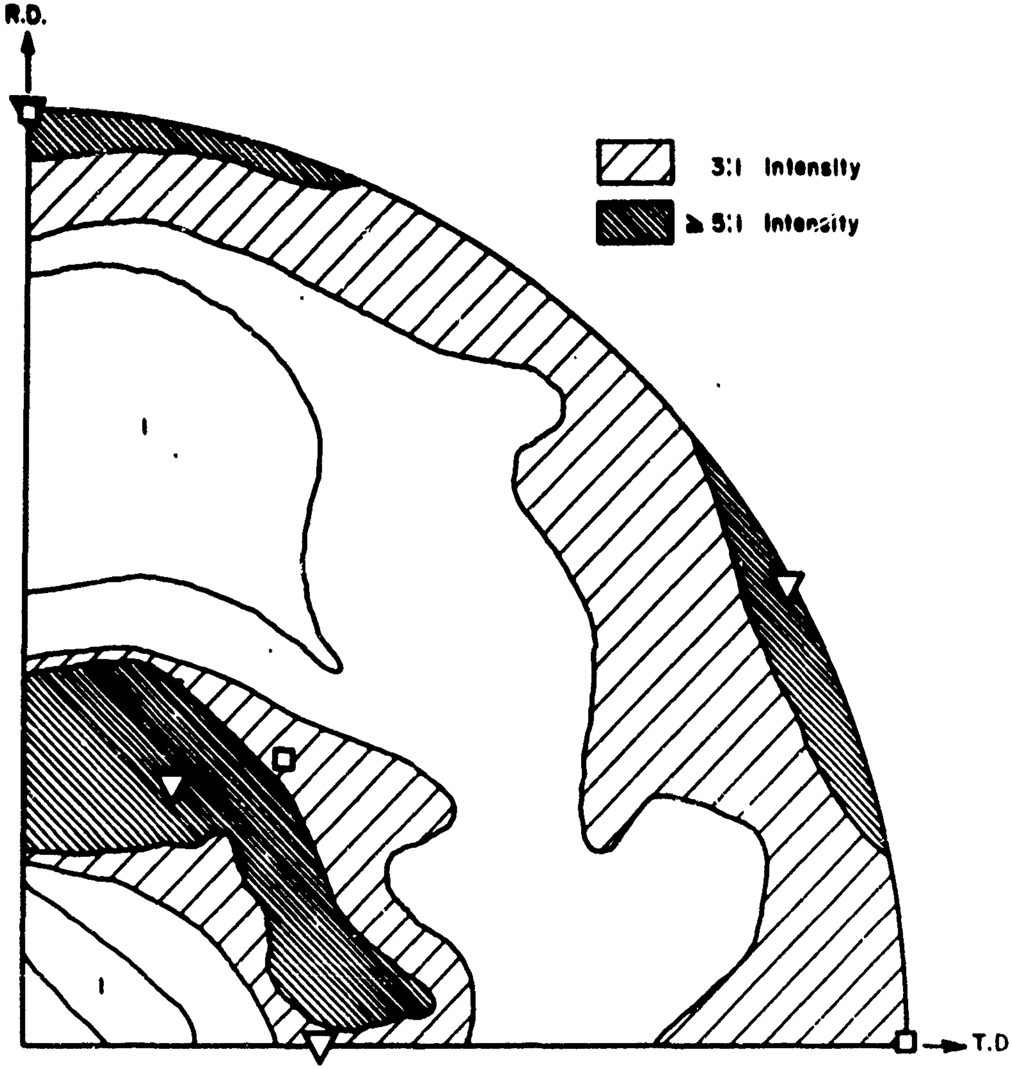
Example of Detailed Intensity Distribution of $\{110\}$ Poles Obtained From Tracing a Spiral Path on the Stereographic Projection. The Numbers Denote Relative Intensities. Only Part of the Spiral is Shown. The Data Are for the Inner Surface of a Flow-Turned Cylinder of B-120 VCA Titanium Alloy

Figure 1



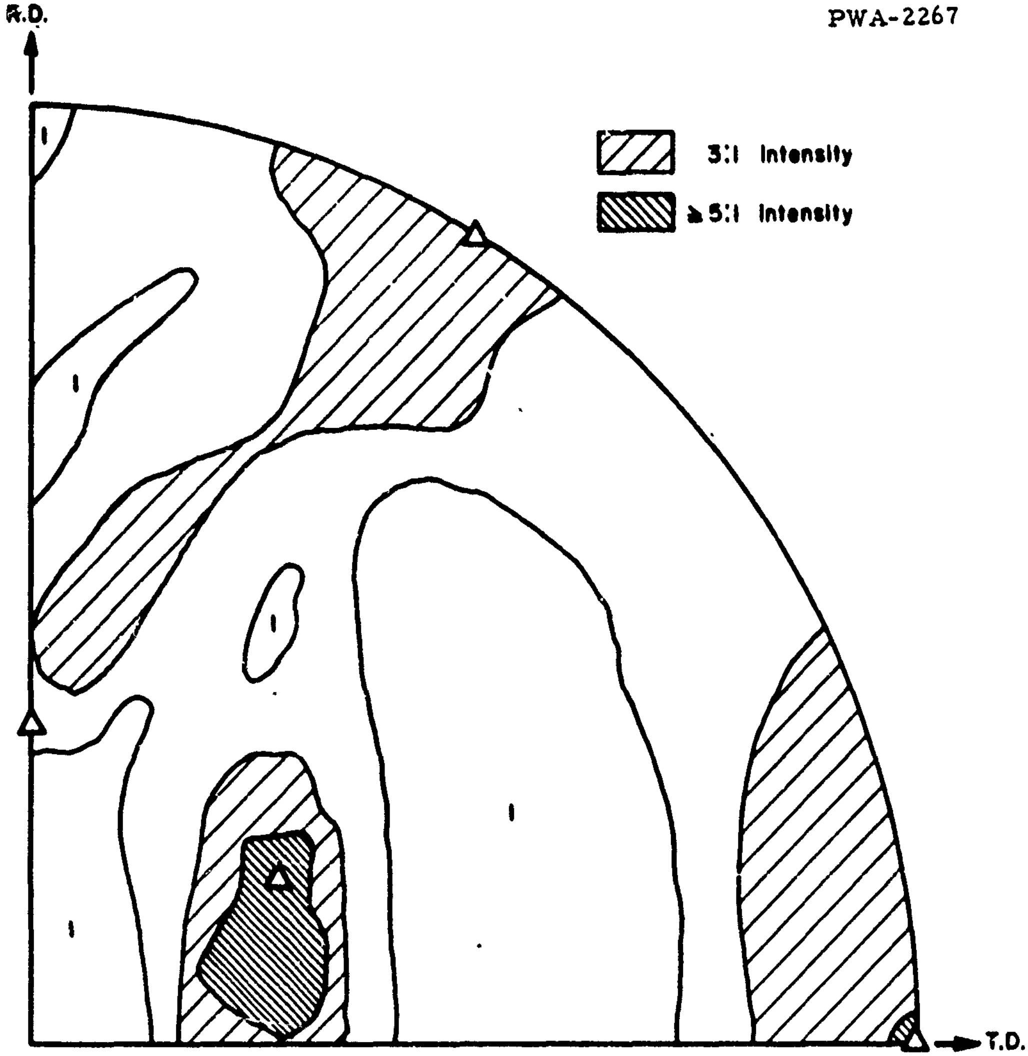
{110} Pole Figure of B-120 VCA Titanium Alloy Sheet, Mill Annealed

Figure 2



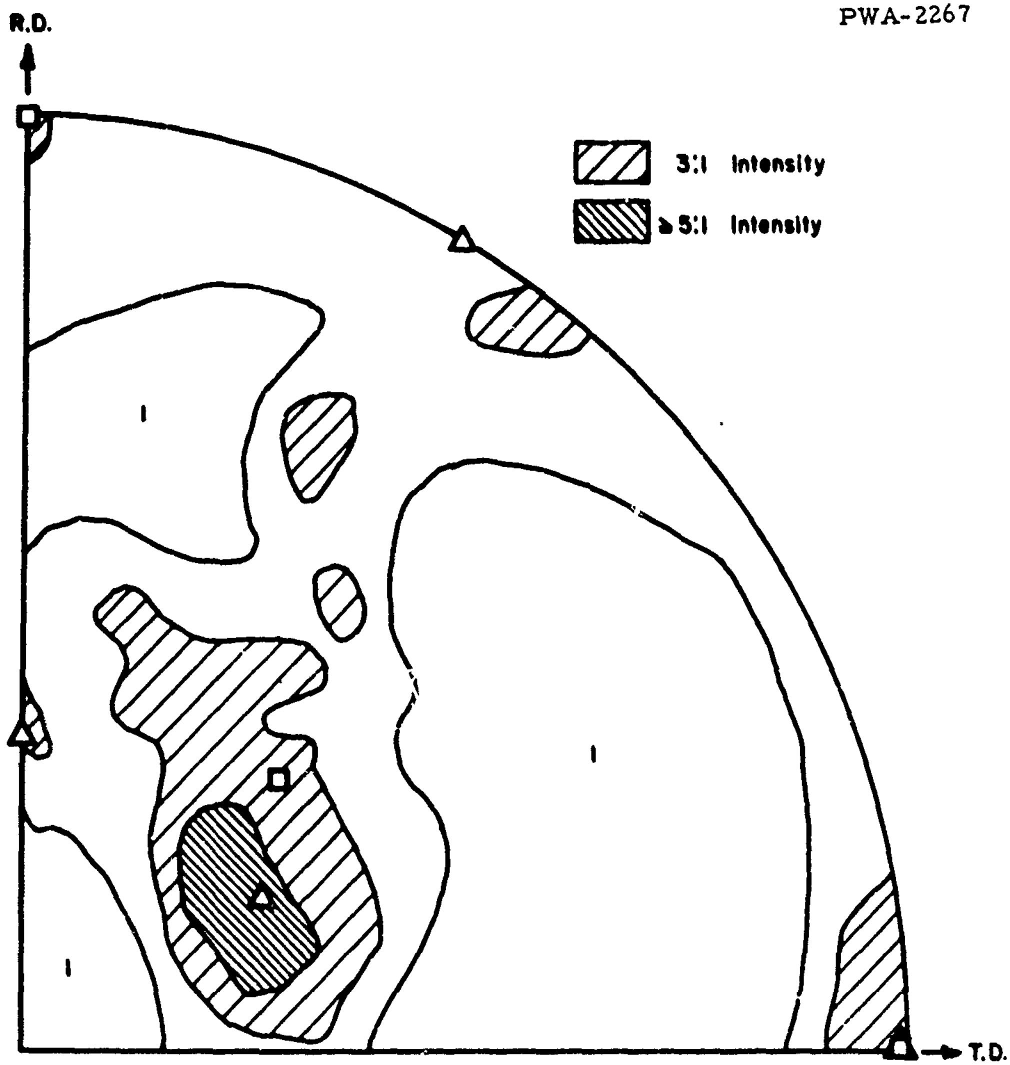
{110} Pole Figure of B-120 VCA Titanium Alloy Cold-Rolled (50% Reduction) and Aged at 850F for 30 Minutes. Nearest Ideal Orientations are Indicated As Follows: □ (100) [011], ▽ (111) [1$\bar{1}$0]

Figure 3



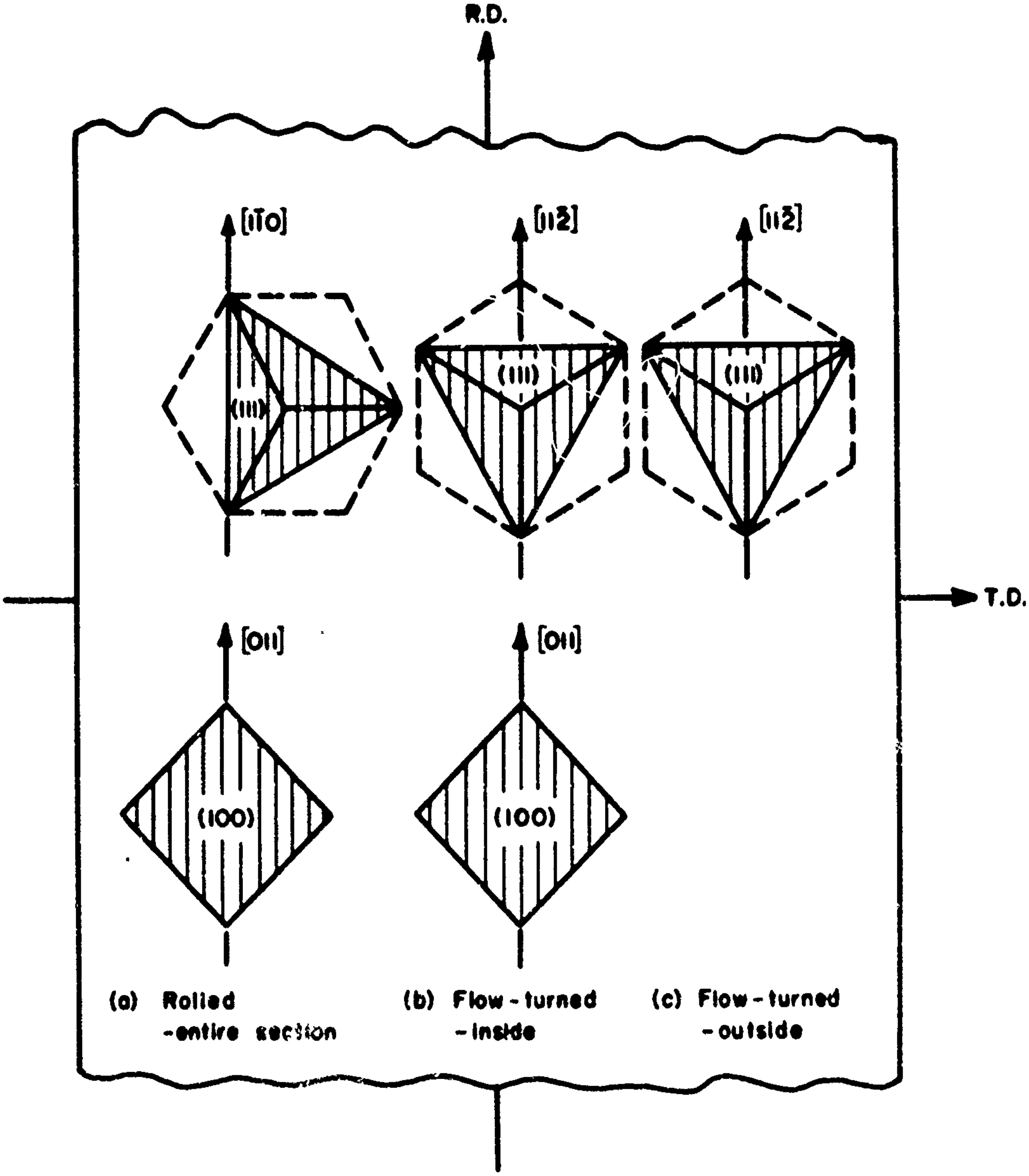
{110} Pole Figure of B-120 VCA Titanium Alloy Flow-Turned (50% Reduction) and Aged at 850F for 30 Minutes for Material Taken From the Outside Portion of the Cylinder. Nearest Ideal Orientations Are Indicated as: Δ (111) [11$\bar{2}$]

Figure 4



{110} Pole Figure of B-120 VCA Titanium Alloy Flow-Turned (50% Reduction) and Aged at 850F for 30 Minutes for Material Taken From the Inside Portion of the Cylinder. Nearest Ideal Orientations Are Indicated as Follows: □ (100) [011] , Δ (111) [11$\bar{2}$]

Figure 5



Model Illustrating Ideal Orientations Observed in Cold-Reduced B - 120 VCA Titanium Alloy. The Surface of the Cold-Reduced Sheet is in the Plane of the Paper

Figure 6

ASTM STANDARD 3 x 12 INCH G_c SPECIMEN USED FOR TESTING FLOW-TURNED B-120VCA TITANIUM ALLOY CYLINDERS

(SPECIMEN 0.080 INCH THICK)

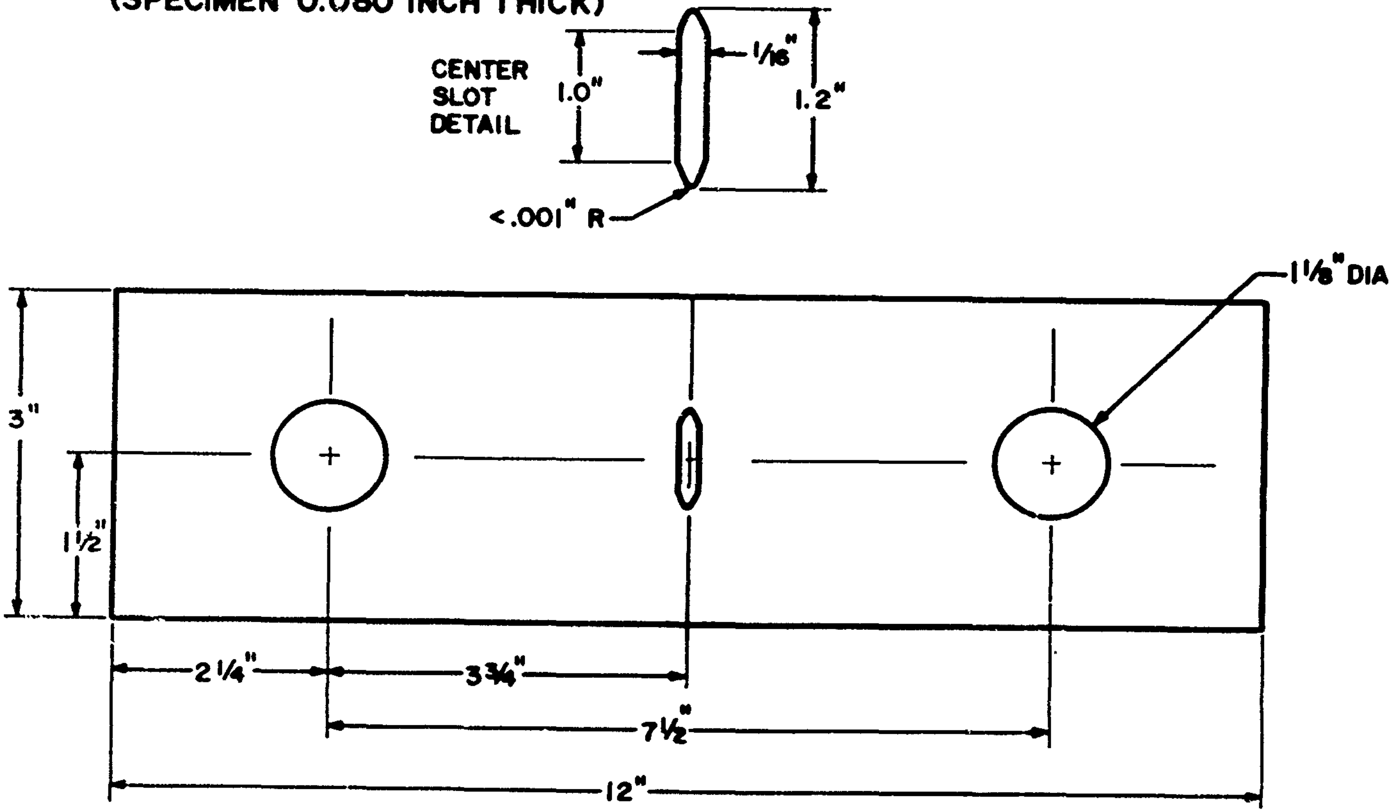


Figure 7

TENSILE SPECIMEN CONFIGURATION EMPLOYED IN EVALUATION OF FLOW-TURNED B-120VCA TITANIUM CYLINDERS

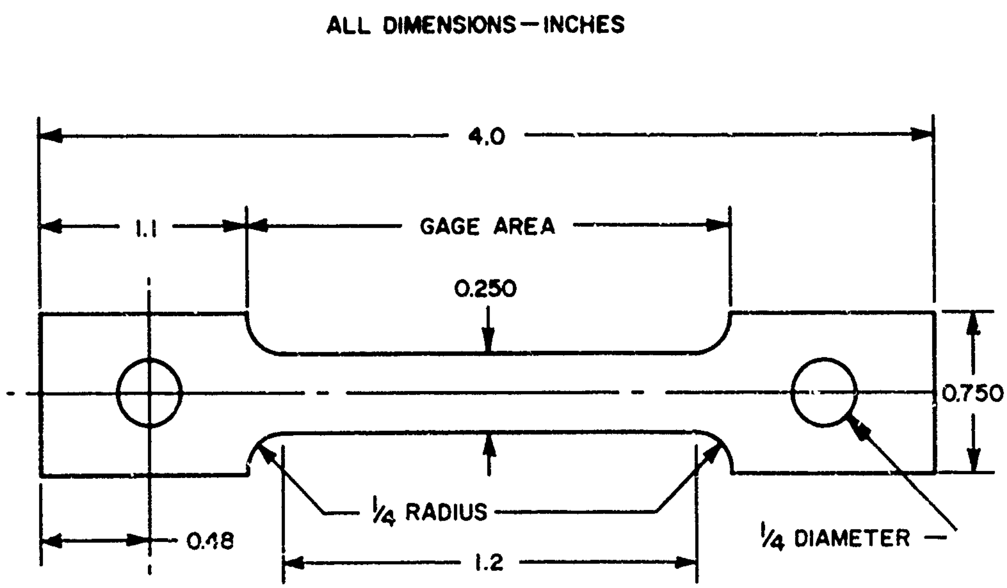


Figure 8

FRACTURE TOUGHNESS (G_c) AND YIELD STRENGTH FOR B-120 VCA PERSHING FLOW-TURNED CYLINDERS

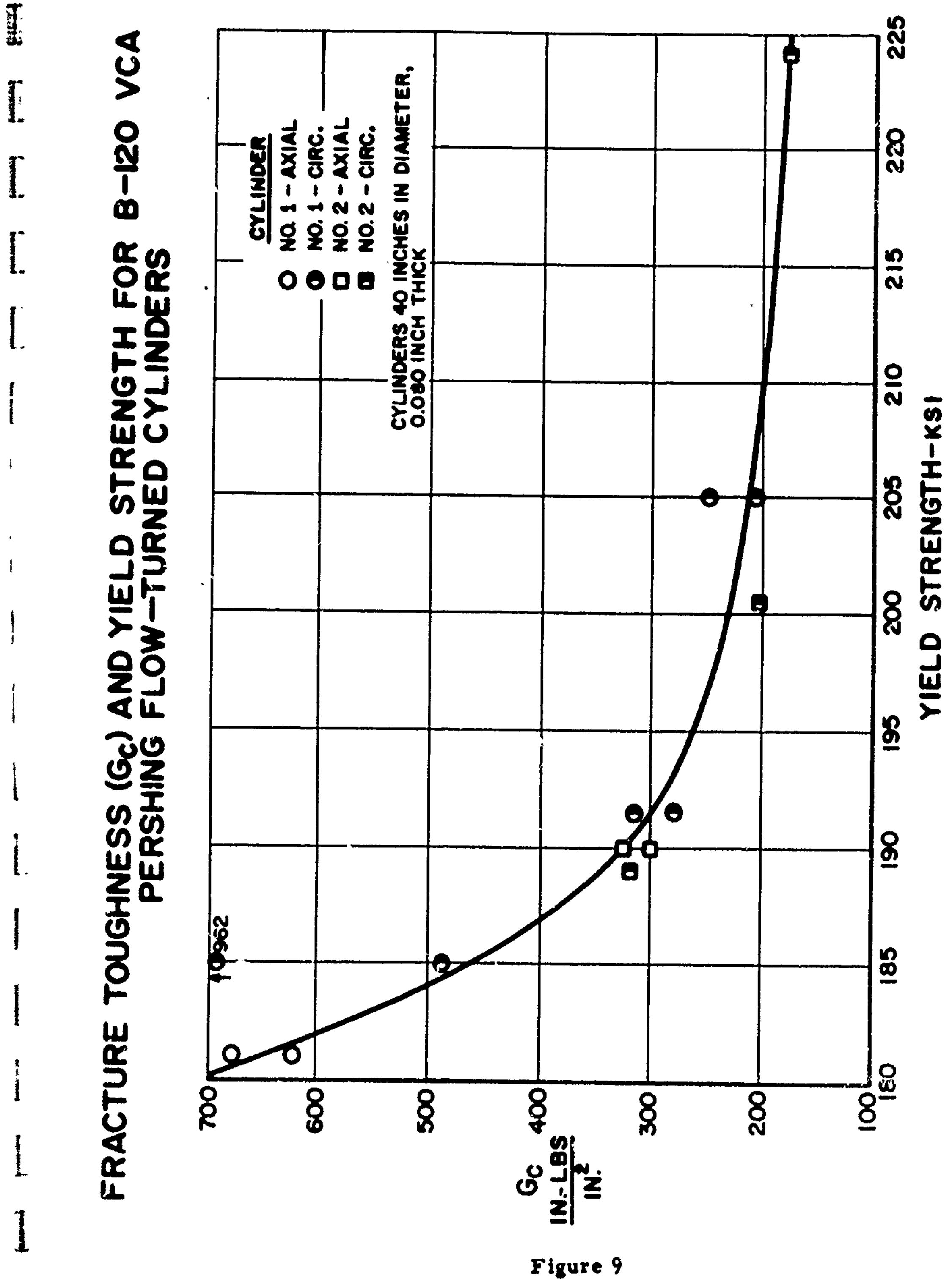


Figure 9

ASTM STANDARD 2 x 8-INCH G_c SPECIMEN USED FOR FRACTURE TOUGHNESS TESTING OF FLOW-TURNED MATERIAL

(SPECIMEN 0.080" THICK)

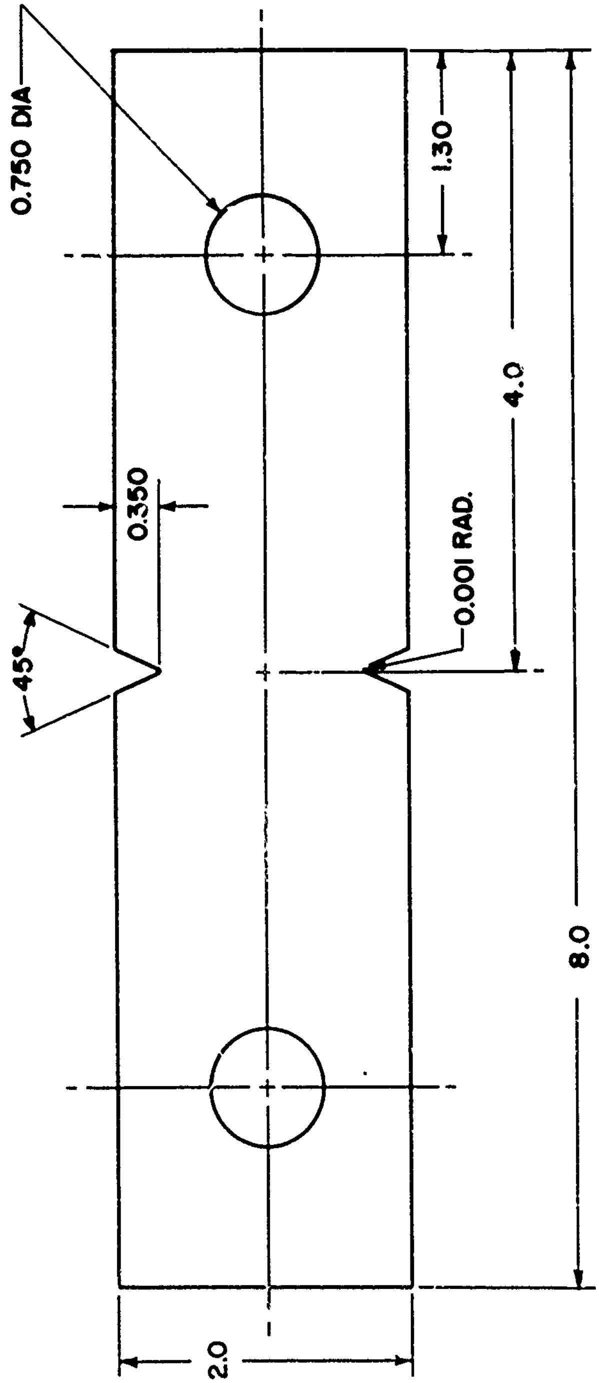


Figure 10

ASTM STANDARD 1 x 4-INCH Gc SPECIMEN USED FOR FRACTURE TOUGHNESS TESTING OF FLOW-TURNED MATERIAL

(SPECIMEN 0.(180" THICK)

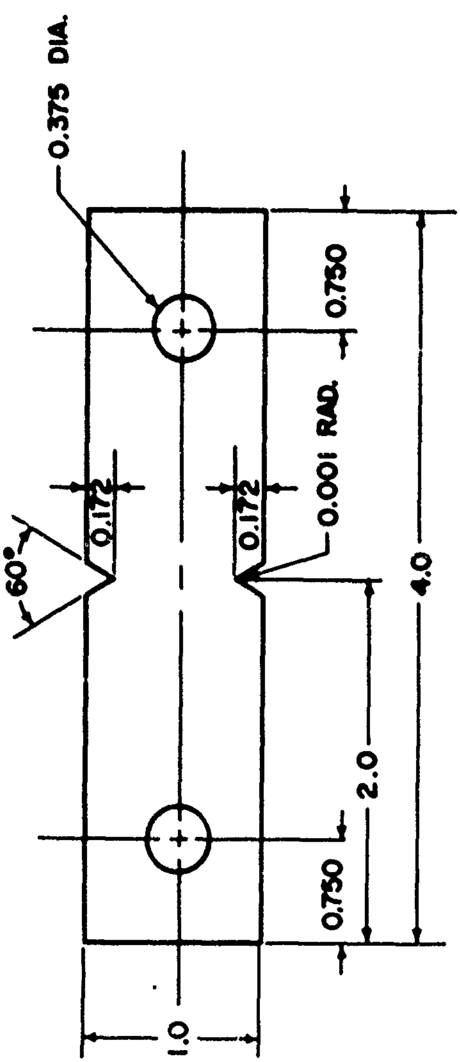


Figure 11

MODIFIED CHARPY IMPACT SPECIMEN
USED FOR FRACTURE TOUGHNESS
TESTING OF FLOW-TURNED MATERIAL

(SPECIMEN 0.080" THICK)

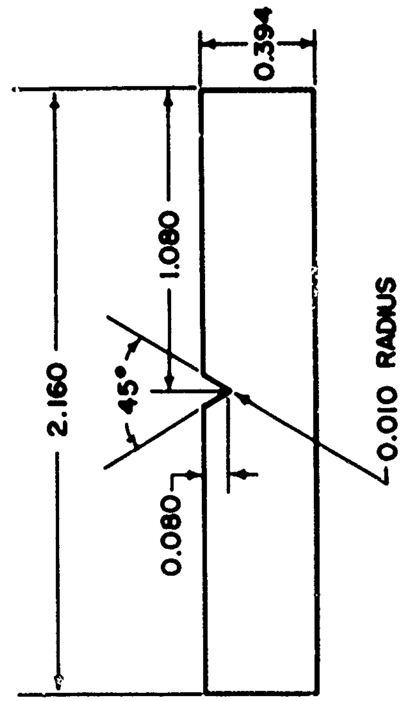


Figure 12

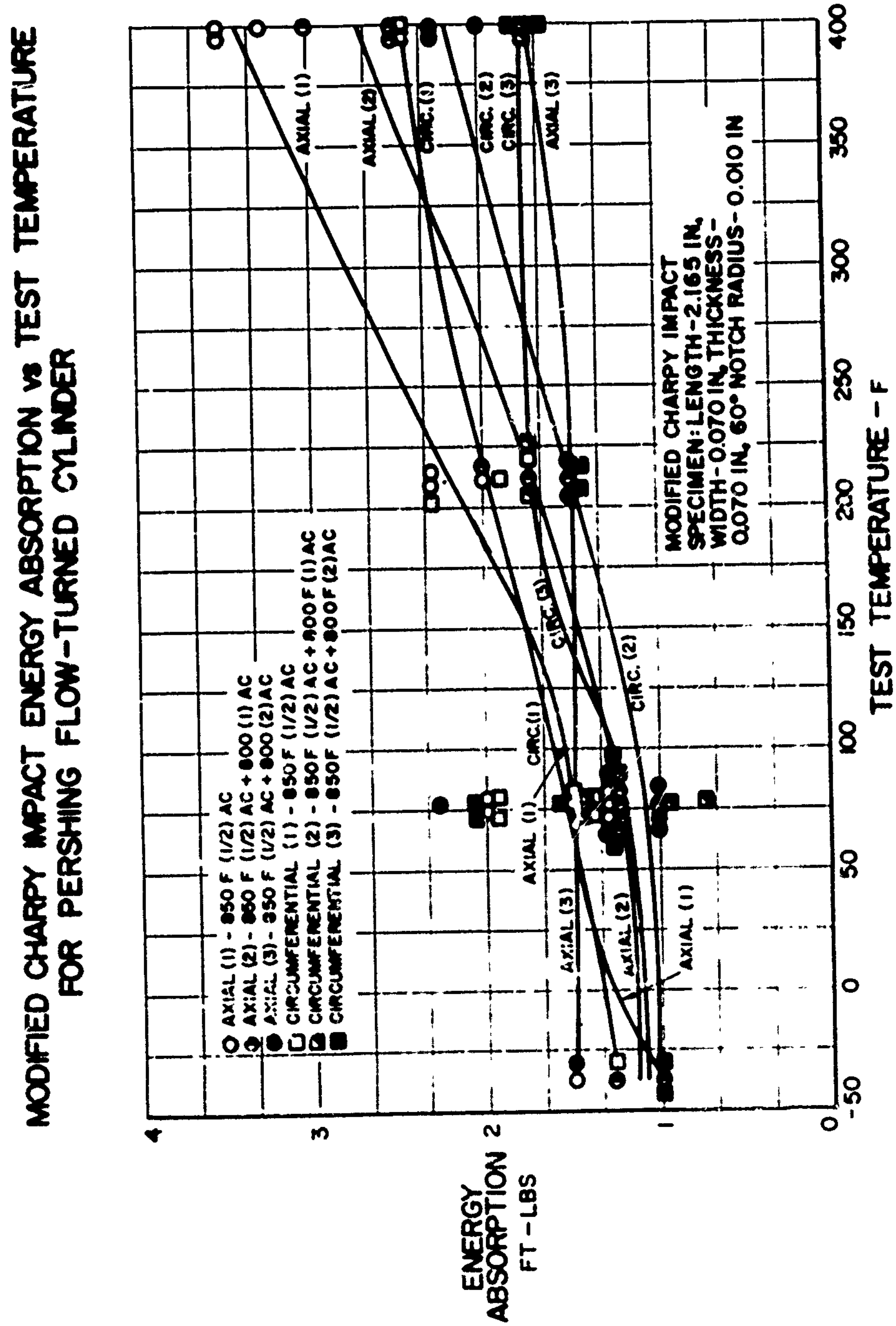

MODIFIED CHARPY IMPACT ENERGY ABSORPTION vs TEST TEMPERATURE
FOR PERSHING FLOW-TURNED CYLINDER
AXIAL (1) - 850 F (1/2) AC
AXIAL (2) - 850 F (1/2) AC + 900 (1) AC
AXIAL (3) - 850 F (1/2) AC + 900 (2) AC
CIRCUMFERENTIAL (1) - 850 F (1/2) AC
CIRCUMFERENTIAL (2) - 850 F (1/2) AC + 900 F (1) AC
CIRCUMFERENTIAL (3) - 850 F (1/2) AC + 900 F (2) AC
AXIAL (1)
AXIAL (2)
AXIAL (3)
CIRC. (1)
CIRC. (2)
CIRC. (3)
MODIFIED CHARPY IMPACT
SPECIMEN: LENGTH-2.165 IN, WIDTH-0.070 IN, THICKNESS-0.070 IN, 60° NOTCH RADIUS-0.010 IN
ENERGY ABSORPTION FT-LBS
TEST TEMPERATURE - F
0
1
2
3
4
-50
0
50
100
150
200
250
300
350
400

Figure 13

MODIFIED CHARPY IMPACT ENERGY ABSORPTION VS. YIELD STRENGTH FOR FLOW-TURNED CYLINDER TESTED AT 215F & 400F

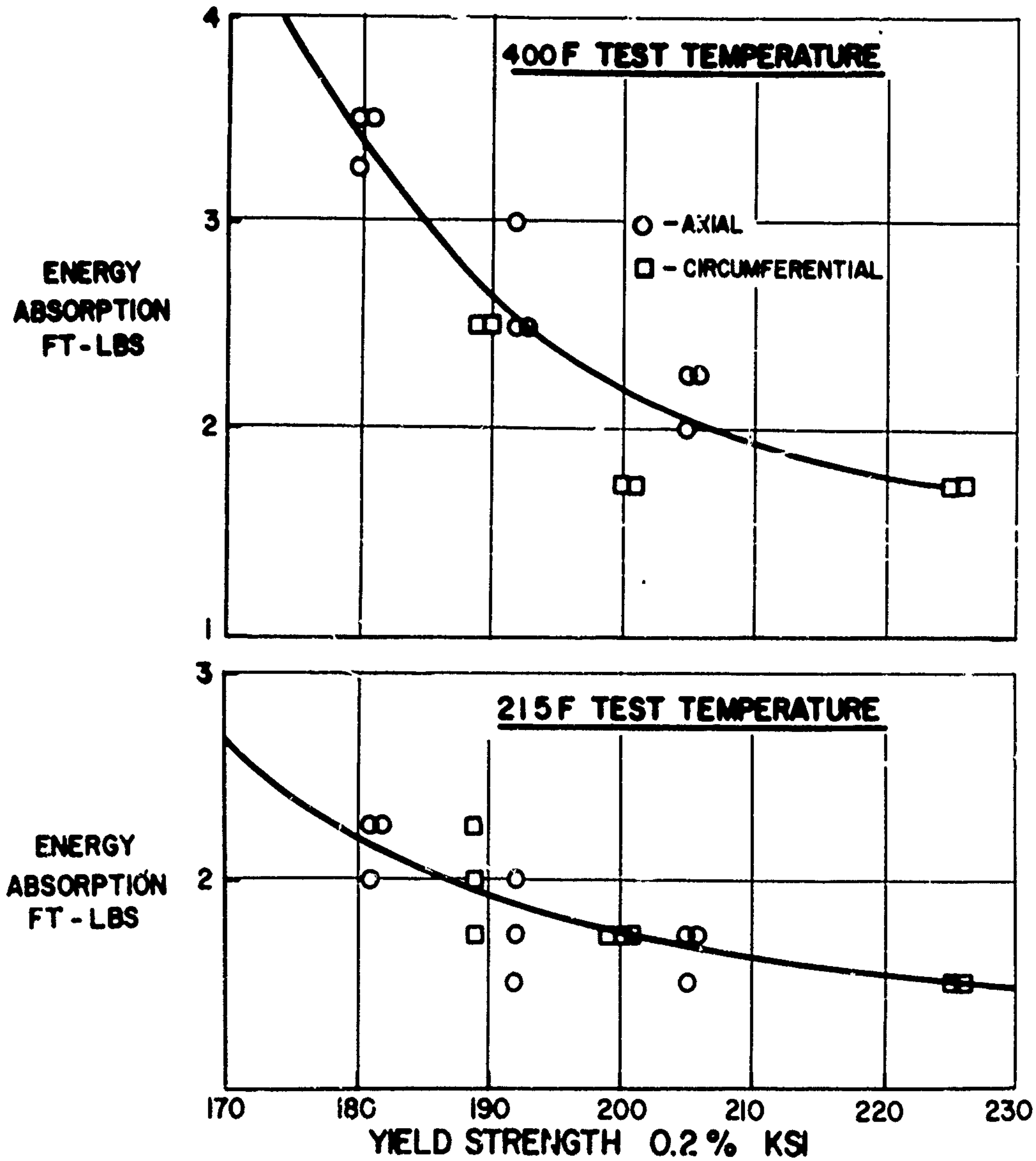


Figure 14

MODIFIED CHARPY IMPACT ENERGY ABSORPTIONS AND YIELD STRENGTHS FOR FLOW-TURNED CYLINDERS TESTED AT 70F AND -35F. SCATTER OF 70F RESULTS PREVENTED ANY CORRELATION.

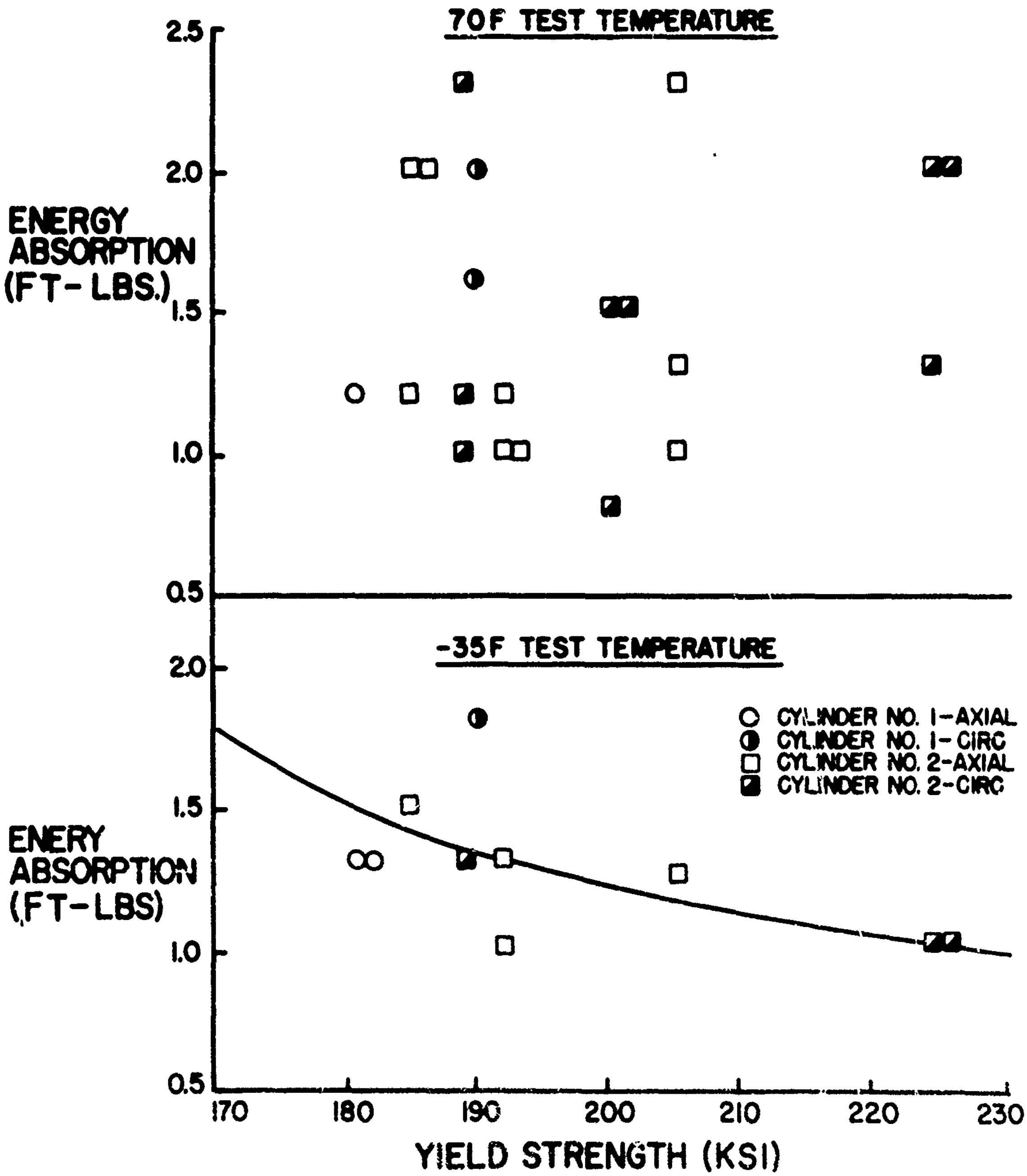
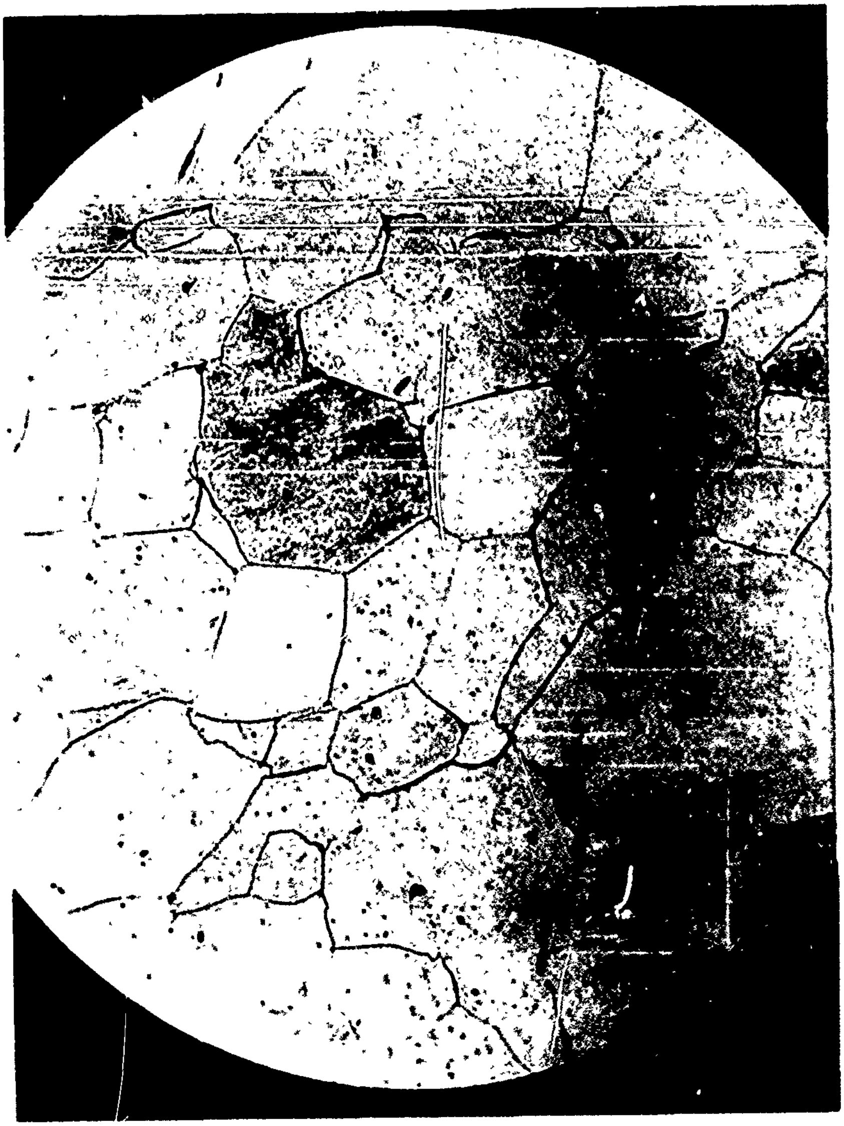


Figure 15



Etchant: 5% HF, 35% HNO_3, 60% H_2O Mag: 100X
Microstructure of Subscale 14-Inch Diameter Rolled Ring Number 5 Heat Treated at 1450F for 15 Minutes During Sizing and Water Quenched

Figure 16

AGING CURVES FOR SUBSCALE 14-INCH DIAMETER RINGS NO. 1, 2 AND 3 ROLLED BY LADISH AT 2000, 1900 AND 1800 F, ANNEALED AT 1450 F AND AGED AT 900 F FOR VARIOUS TIMES

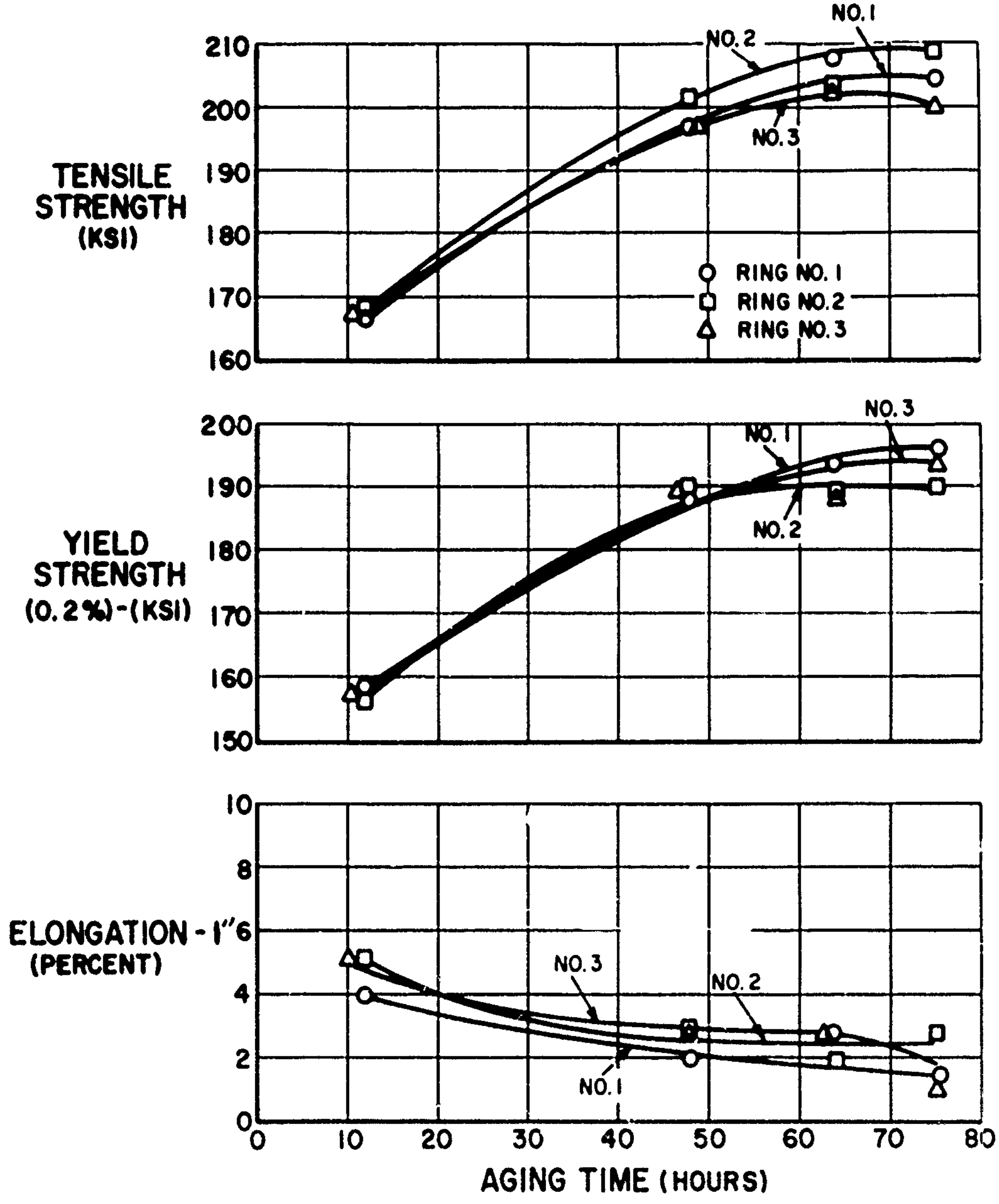


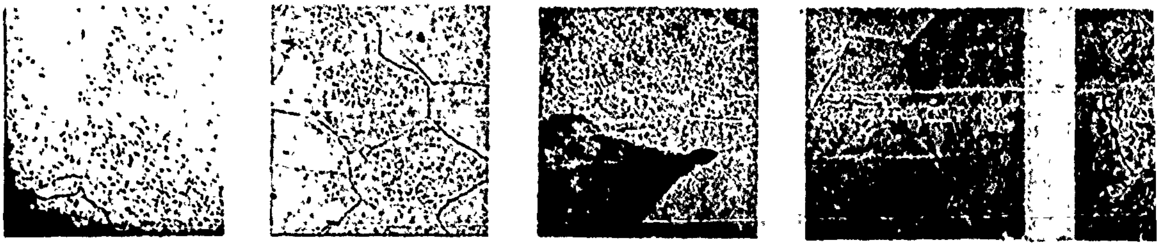
Figure 17

1

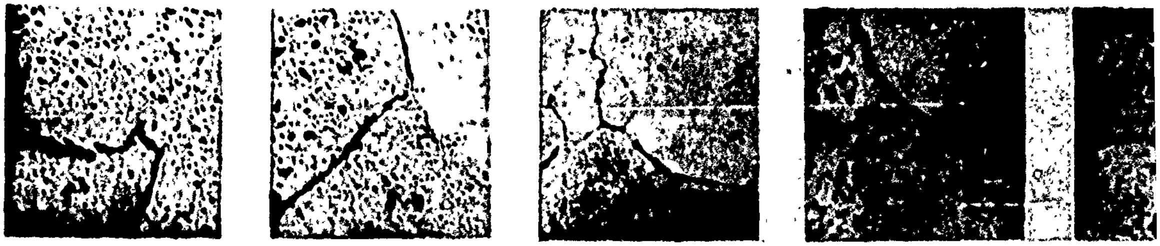
PRECIPITATION STUDY ON 5

AS REC'V'D 900F (2) WQ 1000F (2) WQ 1100F (2) WQ 1200

100 X



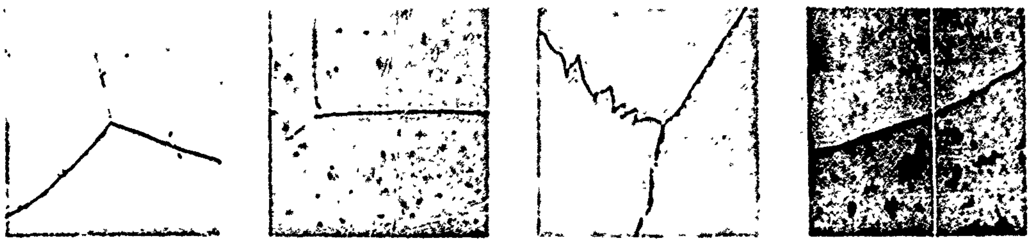
1000 X



1800F (2) WQ 2000F (2) WQ 2100F (2) WQ 1400F (2) SC

100 X

1000 X



*SLOW-COOLED SPECIMENS WERE HEAT TREATED IN THE

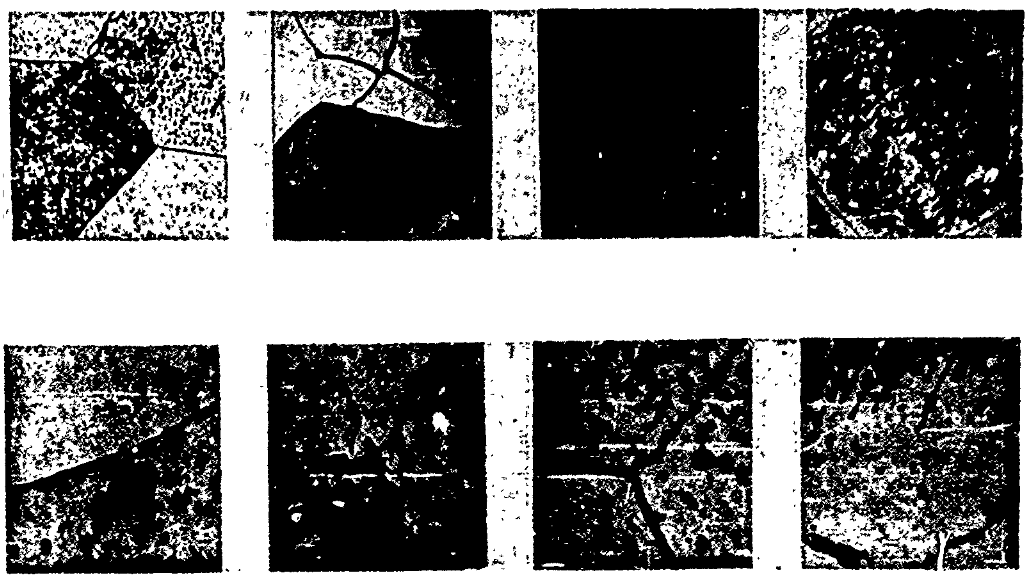
PWA-2267

ION 5 INCH DIAMETER FORGING

(2) WQ 1200F (2) WQ 1300F (2) WQ 1400F (2) WQ 1600F (2) WQ

2

1400F (2) SC* 1600F (2) SC 1800F (2) SC 2000F (2) SC



ATED IN THE CENTER OF 3 1/2×6 INCH ROUND BAR STOCK

Figure 18

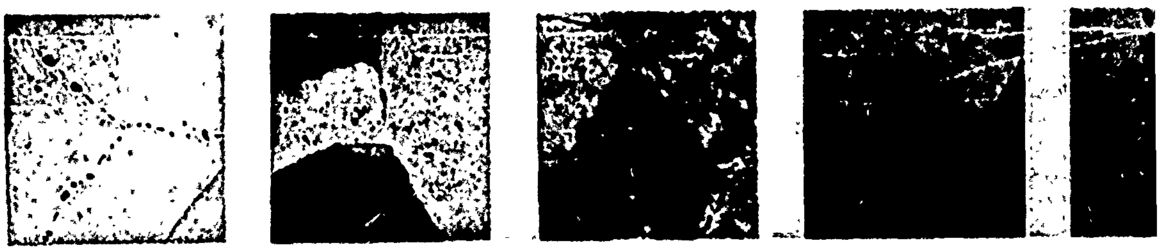
1

PRECIPITATION STUDY ON
ROLL-FORGE

AS REC'V'D 900F (2) WQ 1000F (2) WQ 1100F (2) WQ 1200F

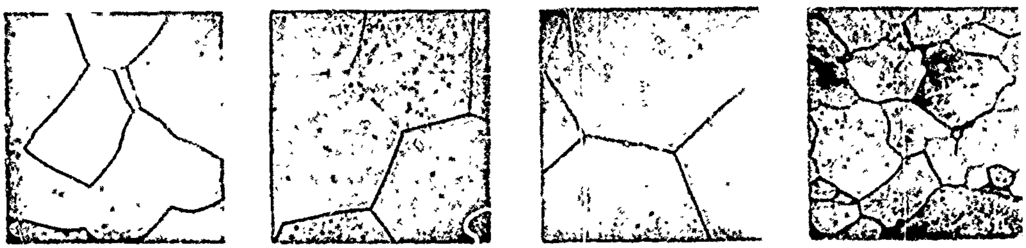
100 X

1000 X



1800F (2) WQ 2000F (2) WQ 2100F (2) WQ 1400F (2) SC

100 X



1000 X

*SLOW-COOLED SPECIMENS WERE HEAT TREATED IN THE

UDY ON 40 INCH DIAMETER FORGED RING

2

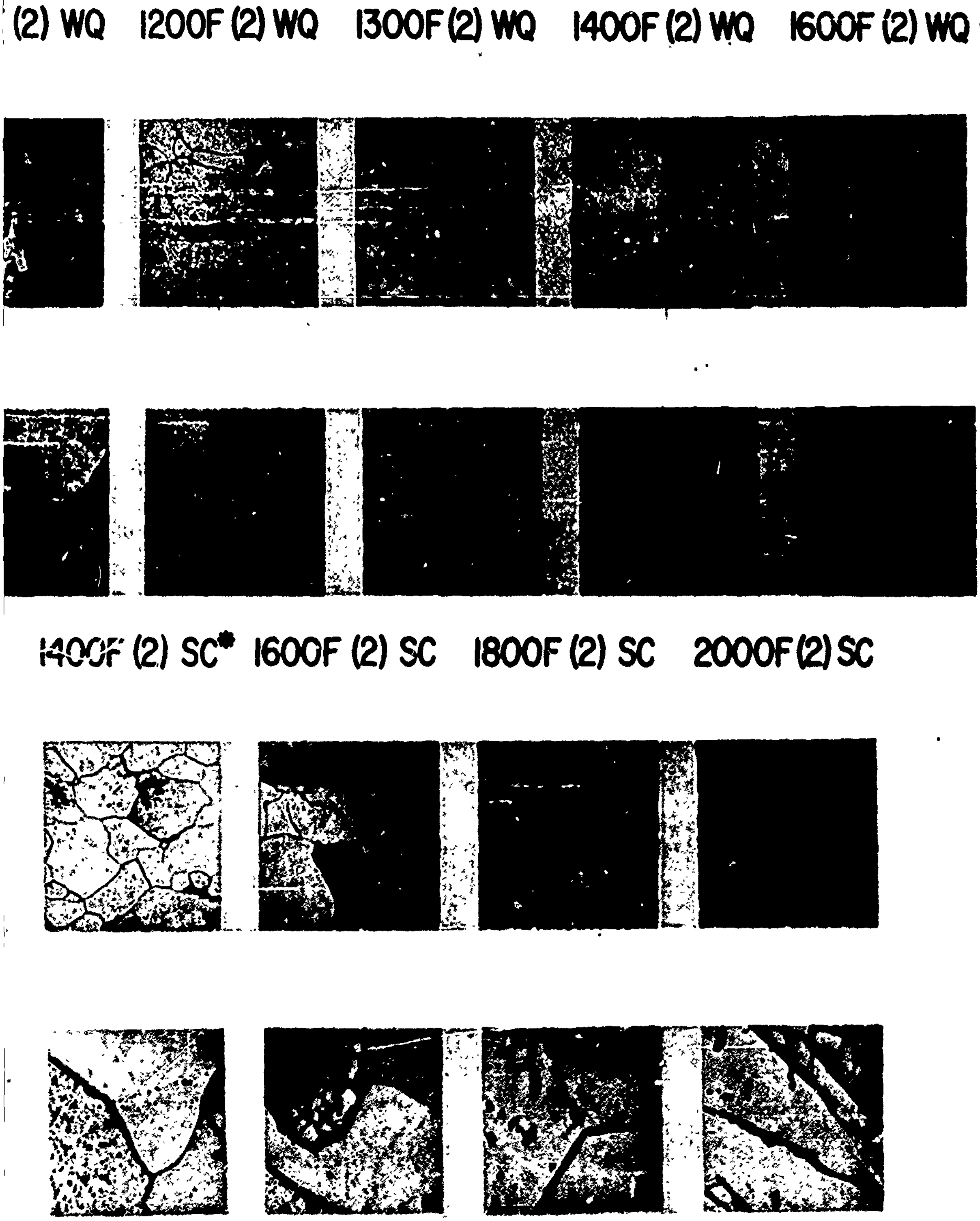
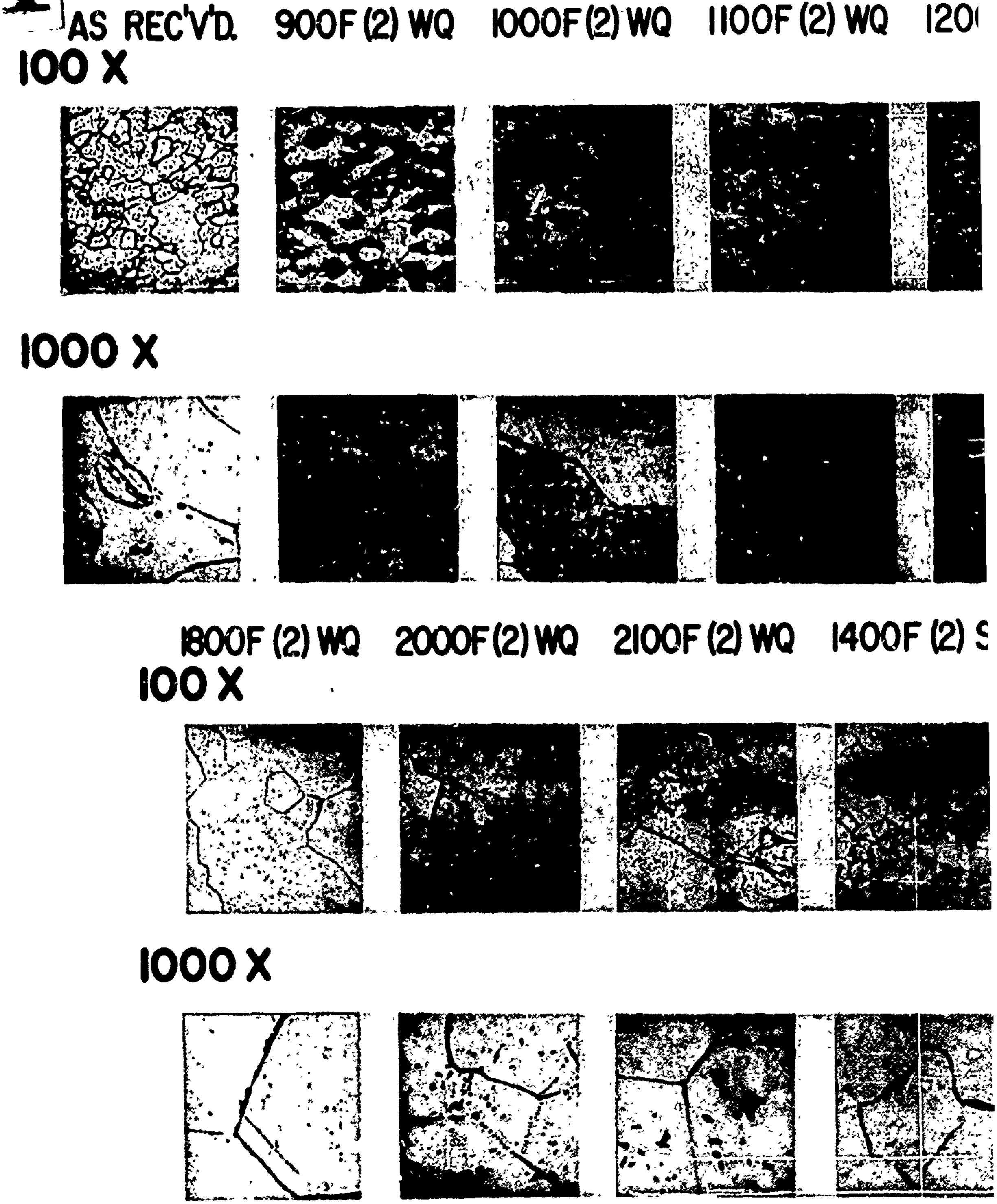


Figure 19

REATED IN THE CENTER OF 3 1/2×6 INCH ROUND BAR STOCK

1

PRECIPITATION STUDY ON
(0.250 INCH

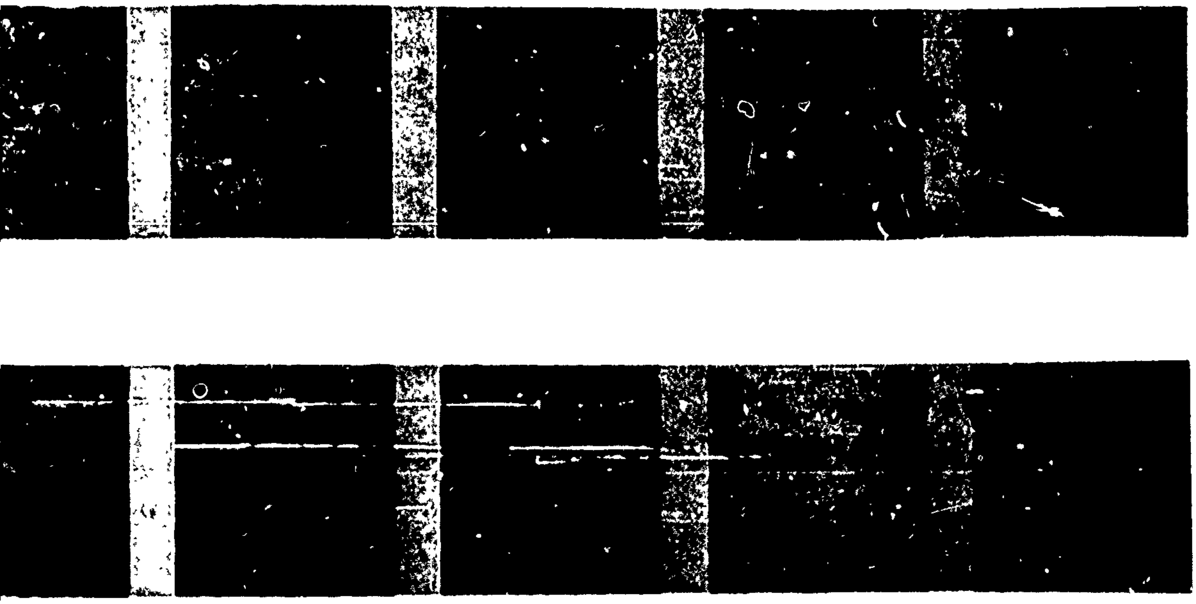


*SLOW-COOLED SPECIMENS WERE HEAT TREATED IN THE

DY ON B120VCA PLATE STOCK
D INCH THICK)

2

F (2) WQ 1200F (2) WQ 1300F (2) WQ 1400F (2) WQ 1600F (2) WQ



Q 1400F (2) SC* 1600F (2) SC 1800F (2) SC 2000F (2) SC

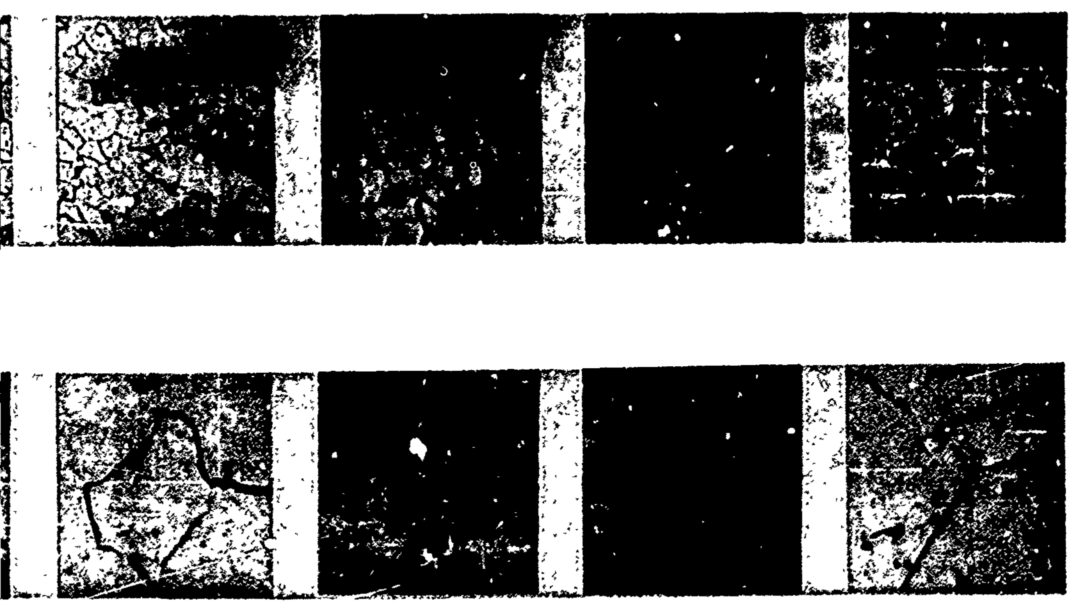
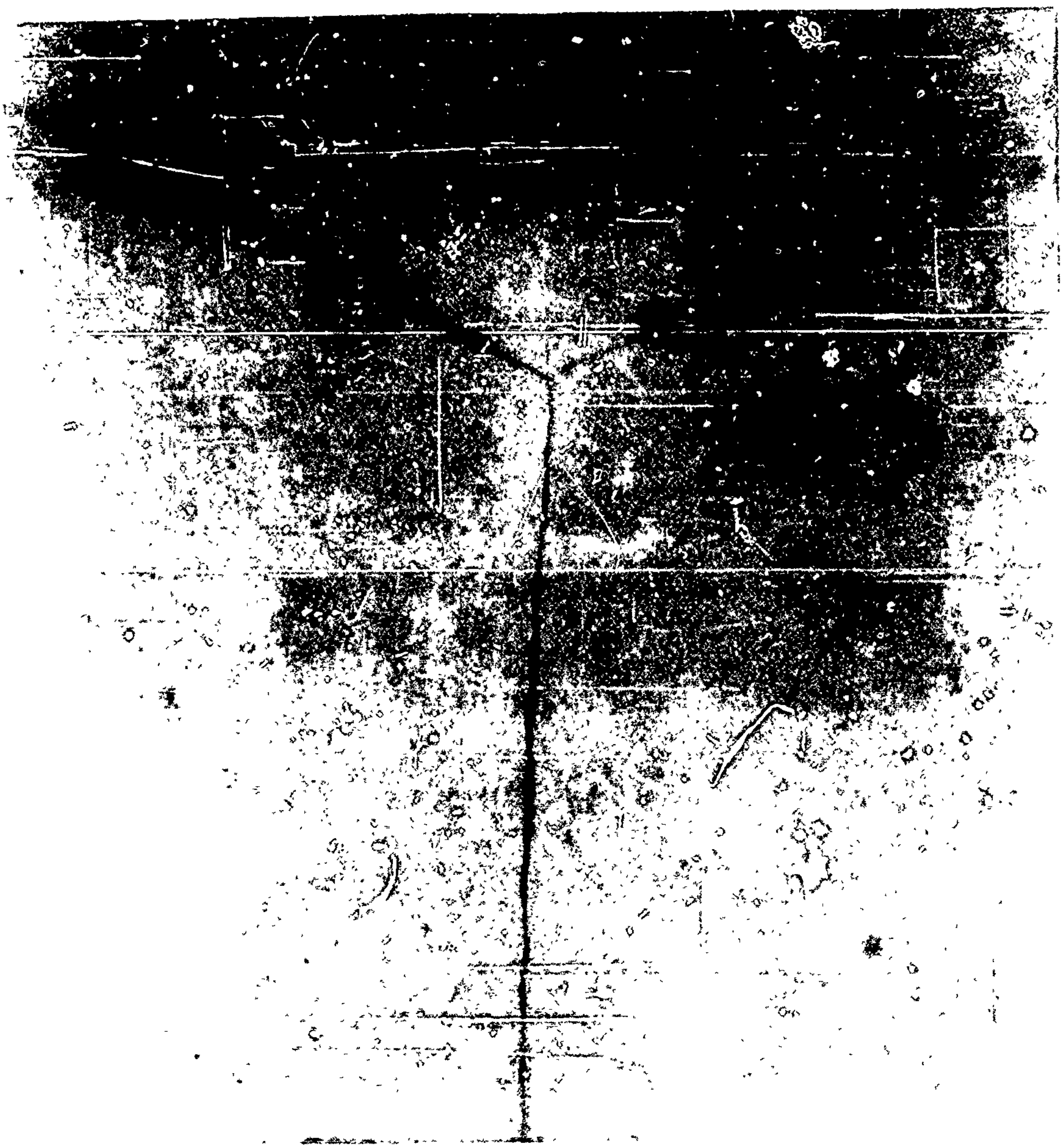


Figure 20

EATED IN THE CENTER OF 3 1/2×6 INCH ROUND BAR STOCK



Etchant: 5% HF, 35% HNO_3, 60% H_2O Mag:1000X

Microstructure of 40-Inch Diameter Roll-Forged Ring After Heating at 2000 F for 2 Hours, Slowly Cooling, and Reheating at 1800 F for 2 Hours Followed by a Water Quench

Figure 21

TENSILE PROPERTIES OF FULL SCALE 40-INCH DIAMETER ROLLED RING SAMPLES AFTER VARIOUS HEAT TREATMENTS AND ALSO AFTER SUBSEQUENT AGING AT 900F

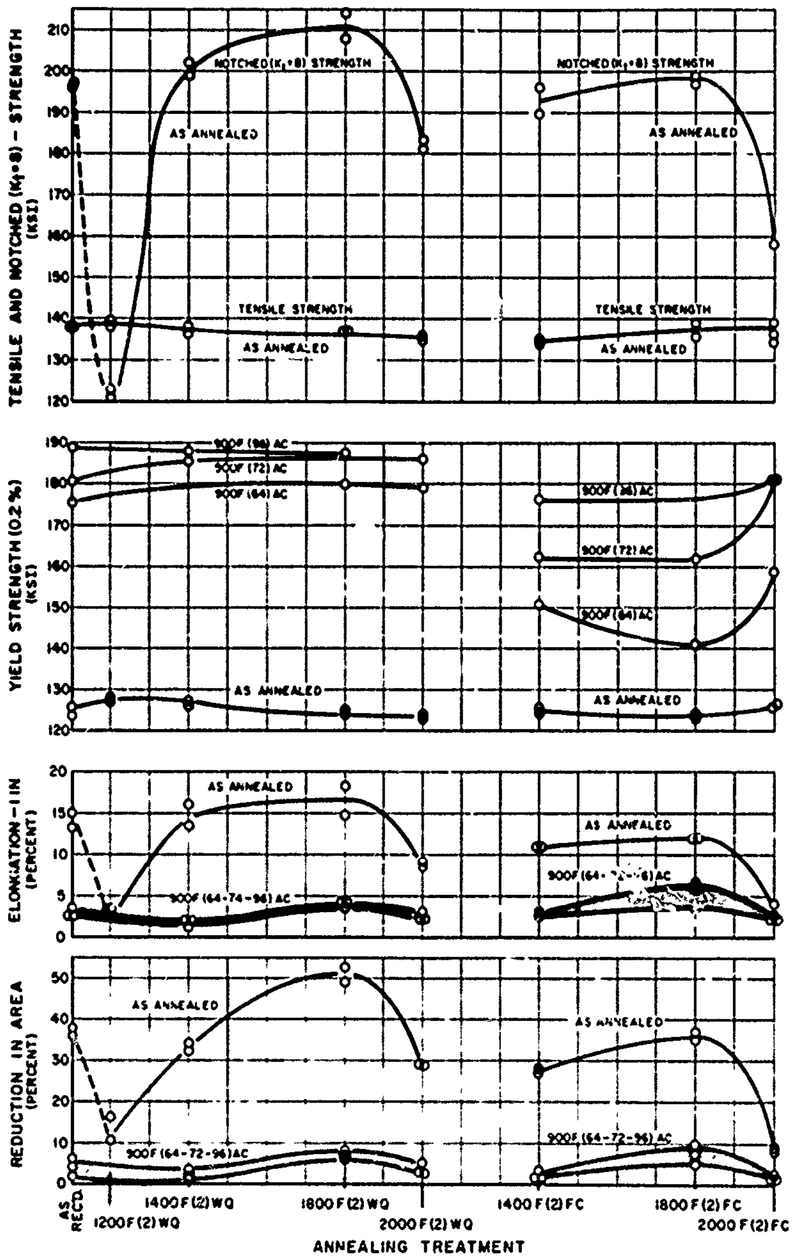
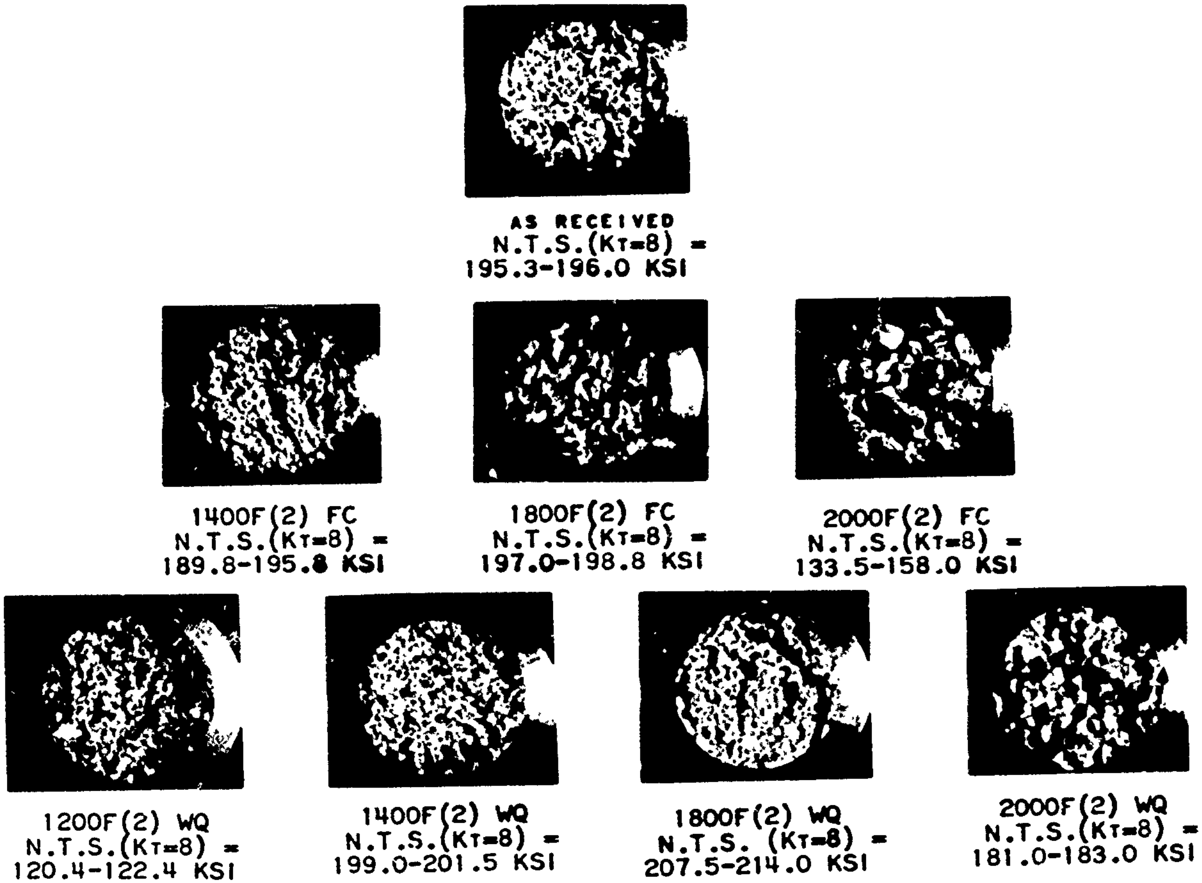


Figure 22



Mag: 3X

Fracture Surfaces of Notched (K_t=8) Specimens From Annealed 40-Inch Diameter Roll-Forged Ring Used in the Determination of the Effect of Heat Treatment on Tensile Properties

Figure 23

AGING CURVES FOR 9.4 - INCH DIAMETER
FLOW - TURNED CYLINDERS
STRESS - RELIEVED AT 850F FOR 30 MINUTES
AND AGED AT 800F.
ONE CYLINDER HAD BEEN MILL - ANNEALED AND
ONE SOLUTION - TREATED AT 1800F
PRIOR TO FLOW - TURNING

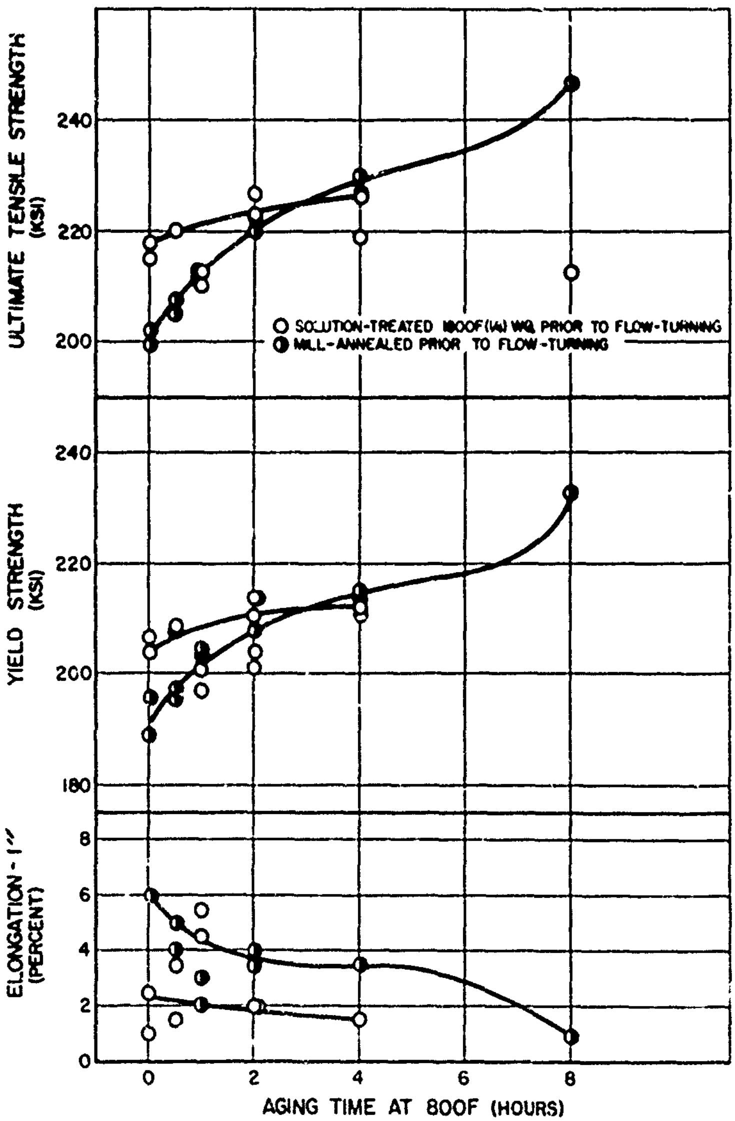
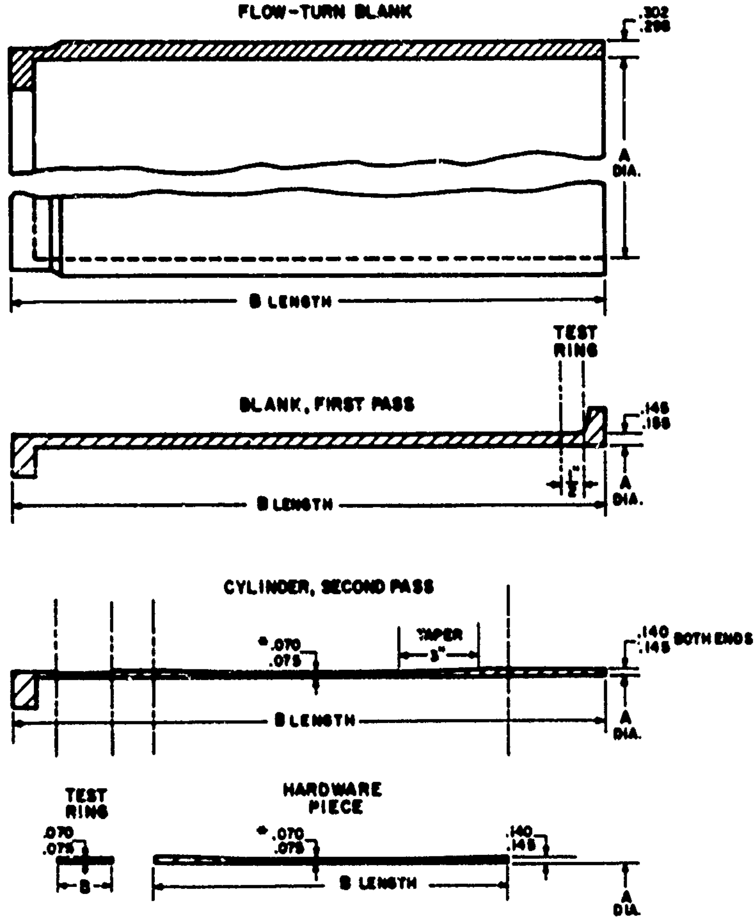


Figure 24

FLOW - TURN SEQUENCES FOR FABRICATING CYLINDRICAL CENTER SECTION



PART	9.4"		14"		40"	
	A	B	A	B	A	B
FLOW-TURN BLANK	9.4"	6	14.125	7	39.622	12.5
BLANK 1st PASS	9.4"	10	14.125	12	39.622	23
BLANK AS FLOW-TURNED	9.4"	18	14.125	21	39.622	35
HARDWARE PIECE	NOT APPLICABLE	NOT APPLICABLE	14.125	NOT APPLICABLE	39.822	26.369
TEST RING	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	39.622	3.50

* FLOW-TURNED TO THIS CONSTANT WALL THICKNESS ON 9.4" DIA. BLANKS

Figure 25

EVOLUTION OF FLOW-TURNING ROLLER CONFIGURATION

FOR B-120 VCA TITANIUM ALLOY

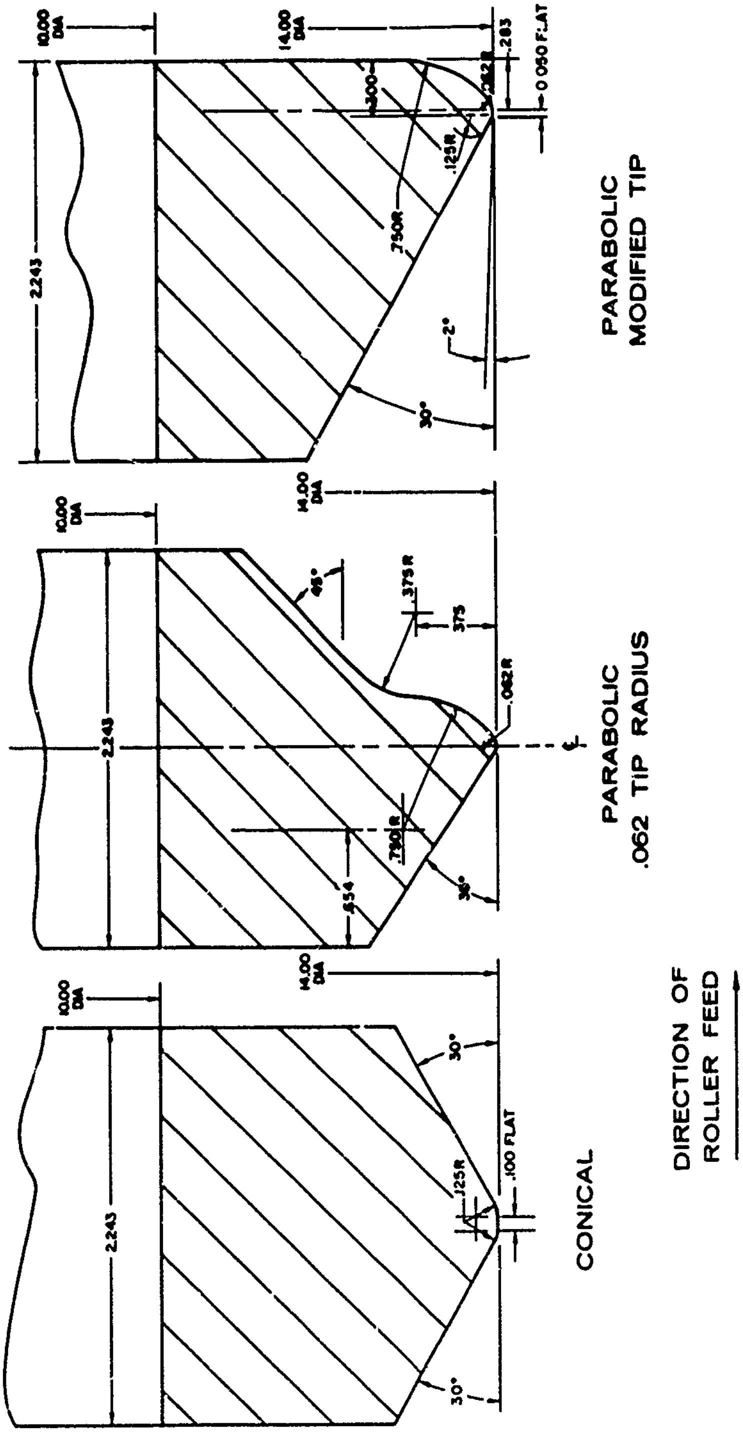
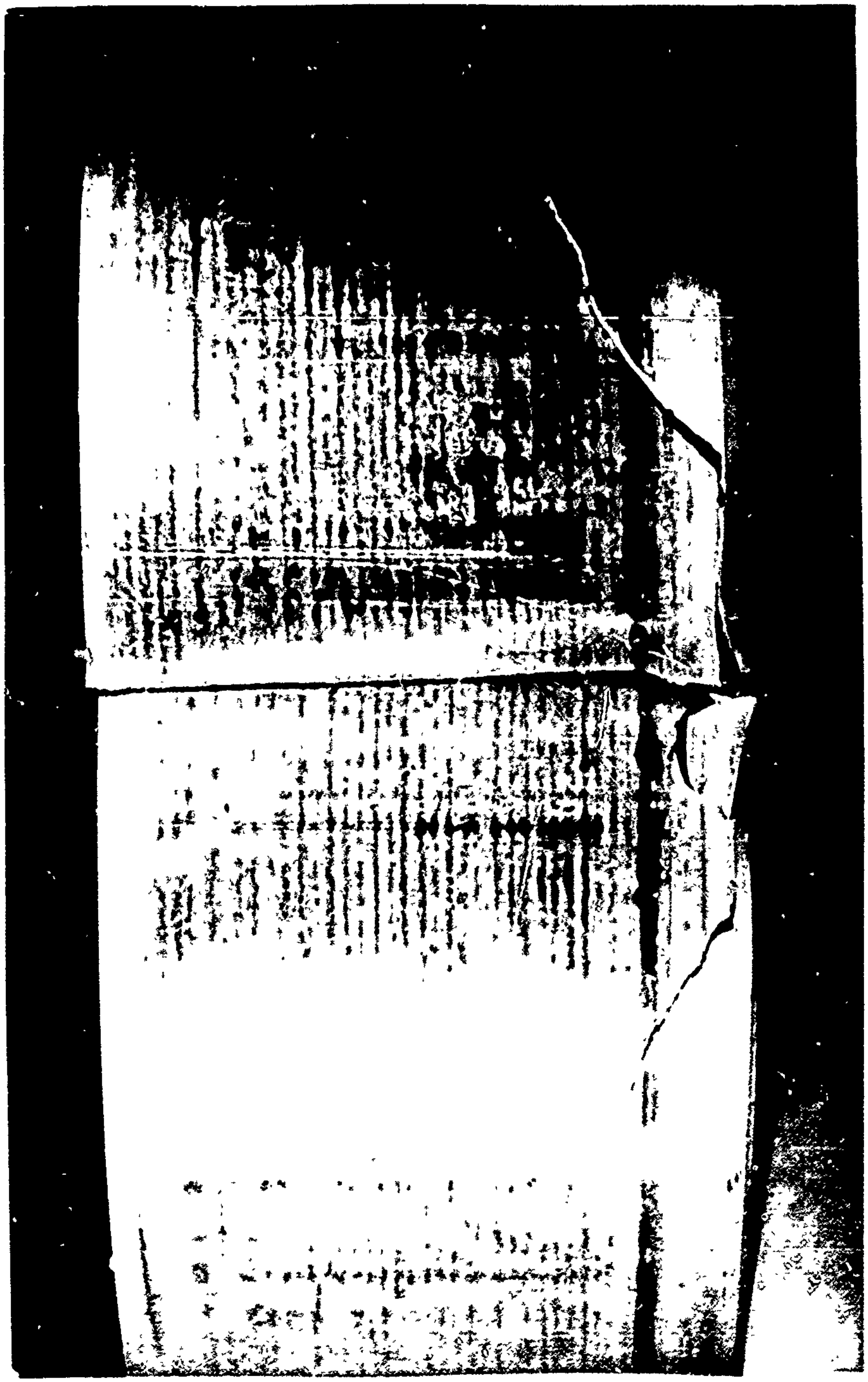
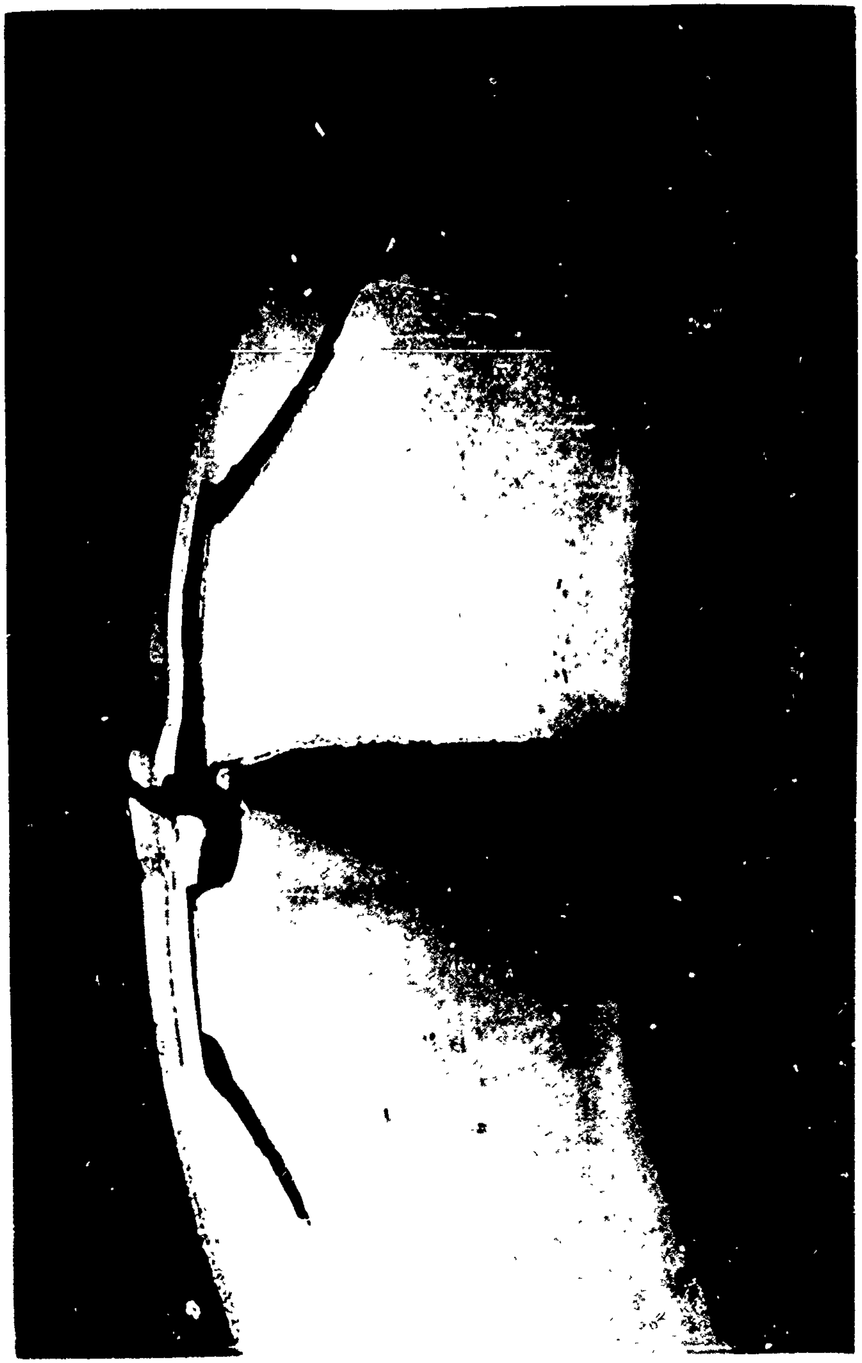


Figure 26



Outside Surface of Full Scale 40-Inch Diameter B-120 VCA Titanium Cylinder Which Failed During the Shrinking Operation

Figure 27



Inside Surface of Full Scale 40-Inch Diameter B-120 VCA Titanium Cylinder Which Failed During the Shrinking Operation

Figure 28

FLOW-TURNING RESULTS WITH CONICAL ROLLER CONTOURS

CINCINNATI TWO ROLLER 40-INCH HYDROSPIN

DIAMETRICAL GROWTH vs. FEED-REDUCTION PARAMETER

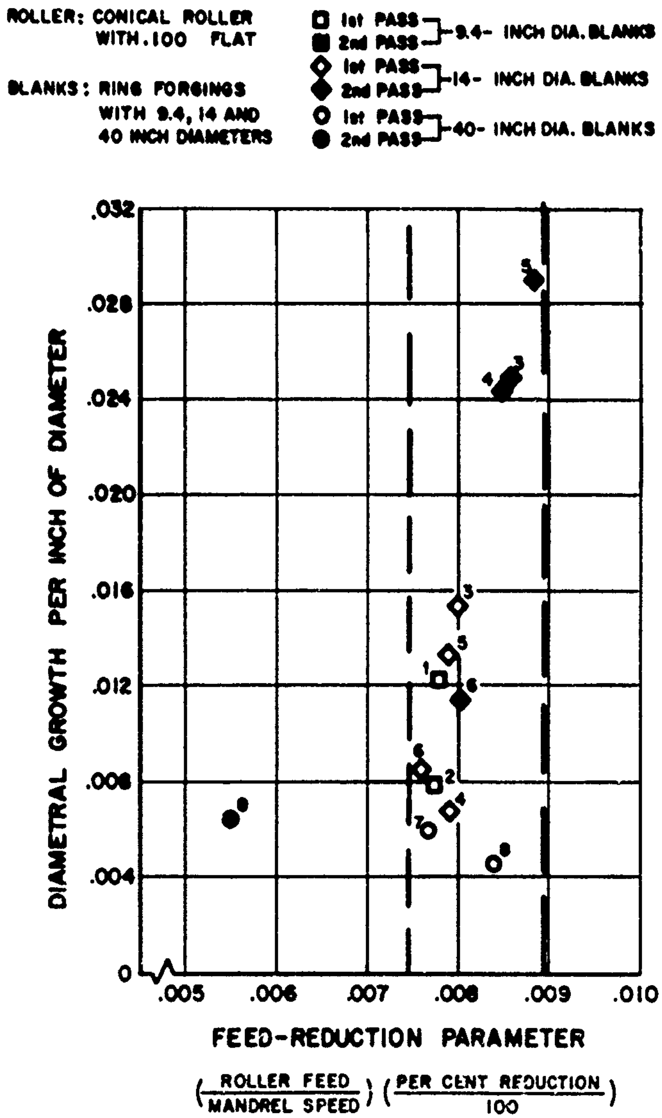
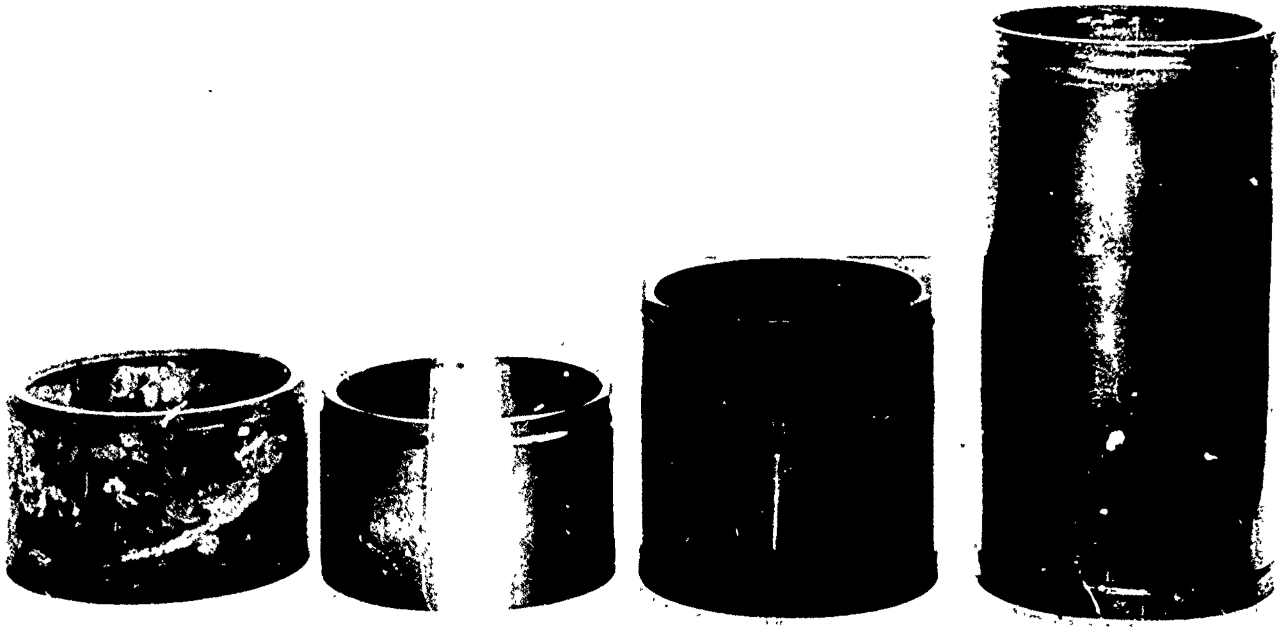


Figure 29



Operations for Flow-Turning B-120 VCA Titanium 14-Inch Diameter Cylinders Made from Rolled and Welded Plate Stock. From Left to Right:

1. Rolled and Welded Blank
2. Machined Blank
3. Cylinder After First Flow-Turning Pass
4. Cylinder After Second Flow-Turning Pass

Figure 30

FLOW-TURNING RESULTS WITH PARABOLIC ROLLER CONTOUR

9.4-INCH DIAMETER ROLLED & WELDED BLANKS DIAMETRAL GROWTH vs. FEED-REDUCTION PARAMETER

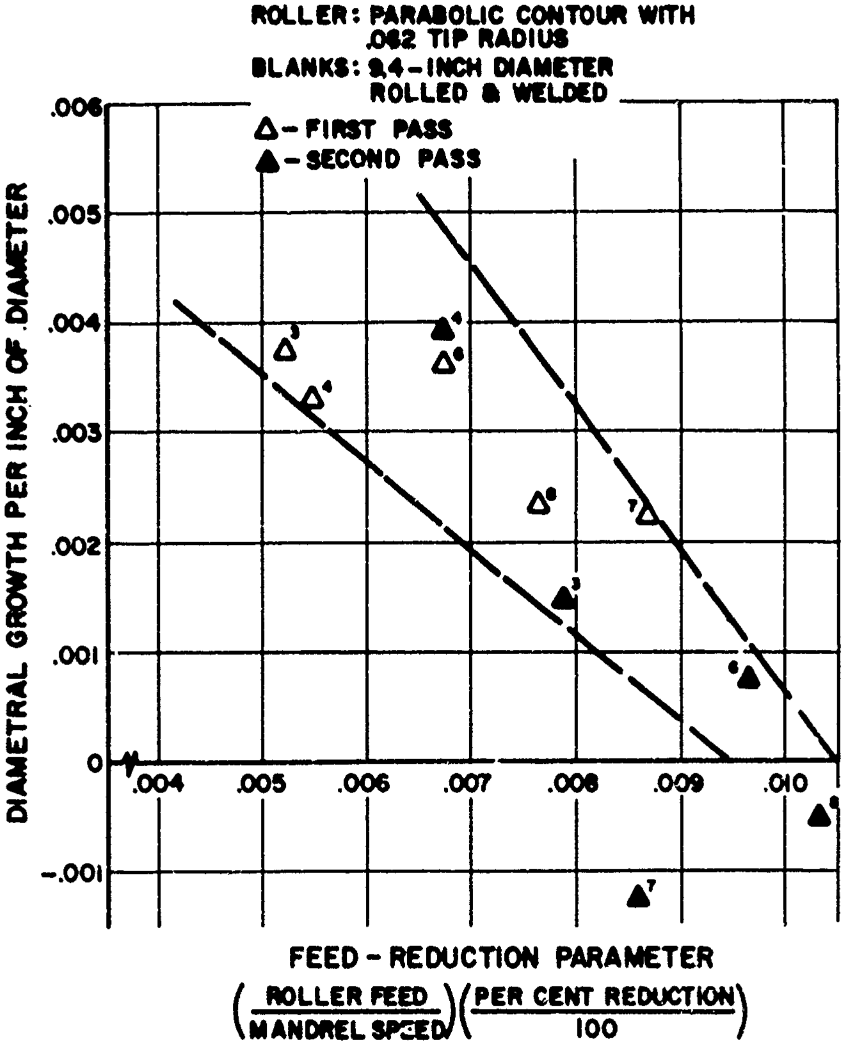


Figure 31

Typical Rolled and Welded Cylinder After First Flow-Turning Pass Showing Condition of Inside Surface and Weld.

Figure 32

Subscale 14-Inch Diameter B-120 VCA Titanium Flow-Turned Cylinder Showing Tears on Inside Surface After the First Pass

Figure 33

Mag: 4X

ubscale 14-Inch Diameter B-120 VCA Titanium Flow-Turned Cylinder Showing Tear (Arrow) on Inside Surface After the First Pass

Figure 34

FLOW-TURNING BEHAVIOR OF 14-INCH DIAMETER ROLLED AND WELDED BLANKS

ROLLER: PARABOLIC CONTOURS WITH
0.062—INCH TIP RADIUS, SHARP
0.062—INCH TIP RADIUS, MODIFIED
0.100—INCH TIP RADIUS
0.220—INCH TIP RADIUS

BLANK: 14-INCH DIAMETER RING FORGING

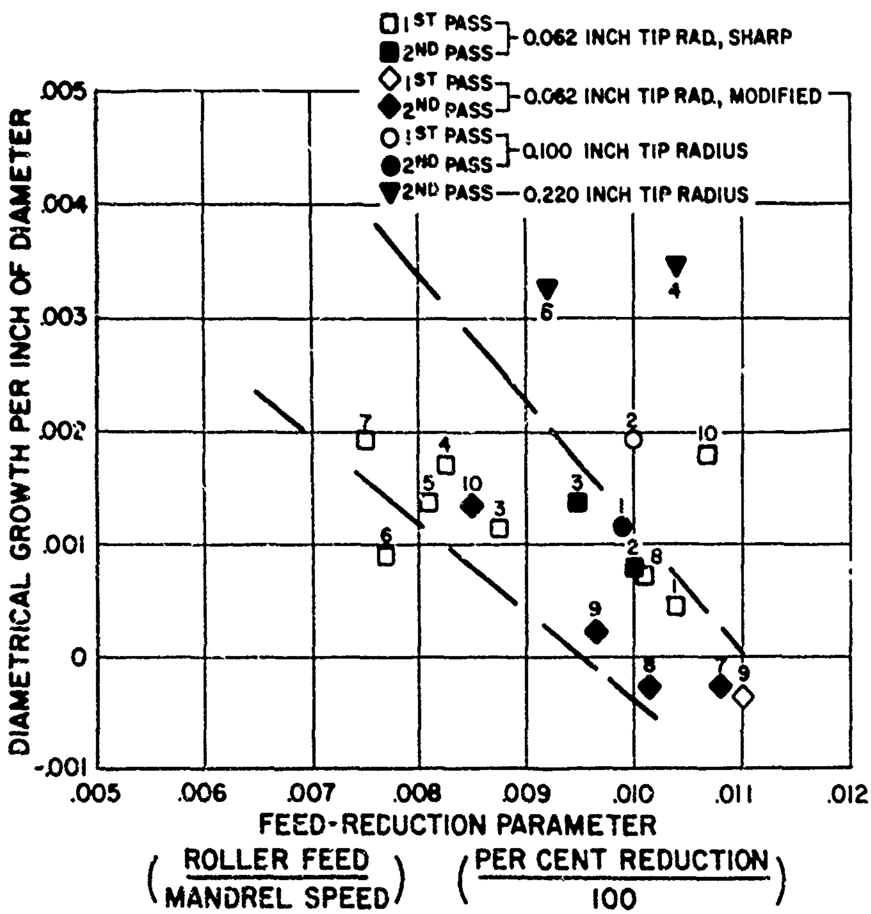
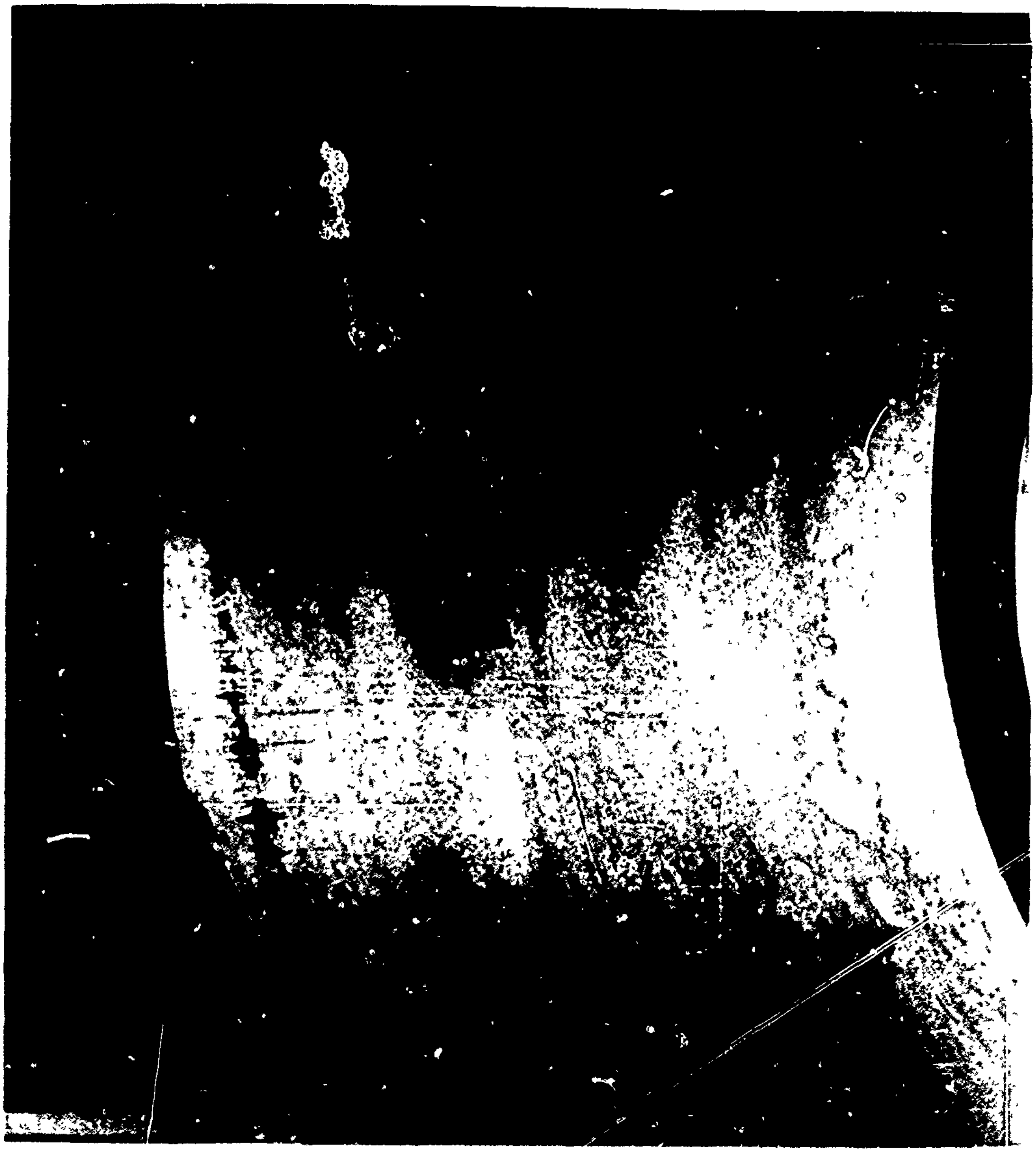


Figure 35



Subscale 14-Inch Diameter B-120 VCA Titanium Roll-Forged Blank Number 6. Note Pitting on Inside Surface After the First Pass

Figure 36

Fourteen-Inch Diameter B-120 VCA Titanium Alloy Forged Cylinder Number 7 After First Flow-Turn Pass. Polished Area Was Blended to Simulate Removal of an Inside Surface Defect 0.025 Inch Deep

Figure 37

Fourteen-Inch Diameter B-120 VCA Titanium Alloy Forged Cylinder Number 7 After Second Flow-Turn Pass. Circle Encloses Area Blended Prior to Second Pass to Simulate Removal of Inside Surface Defect 0.025 Inch Deep

Figure 38

Fourteen-Inch Diameter B-120 VCA Titanium Alloy Forged Cylinder Number 7 After Second Flow-Turn Pass. Circle Encloses Area Blended Prior to Second Pass to Simulate Removal of Inside Surface Defect 0.025 Inch Deep

Figure 38

Mag: 1/4X

Intact (Top) and Axially Cut (Bottom) Sections of As-Flow-Turned 9.4-Inch Diameter B-120 VCA Titanium Alloy Cylinder

Figure 40

CIRCUMFERENTIAL RESIDUAL STRESS DISTRIBUTION THROUGH THE WALL THICKNESS OF 9.4-INCH DIAMETER B-120VCA TITANIUM ALLOY AS-FLOW-TURNED CYLINDER

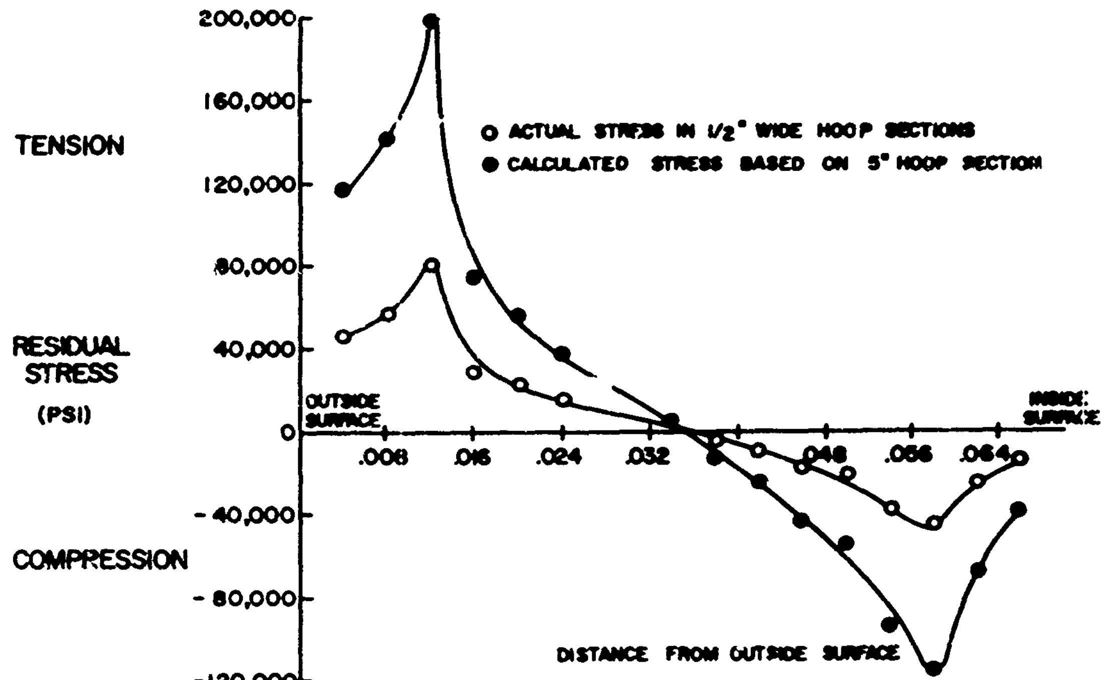


Figure 41

AGING RESPONSE OF 9.4-INCH DIAMETER B-120 VCA TITANIUM ALLOY RING-ROLLED FORGING REDUCED 50% BY FLOW-TURNING

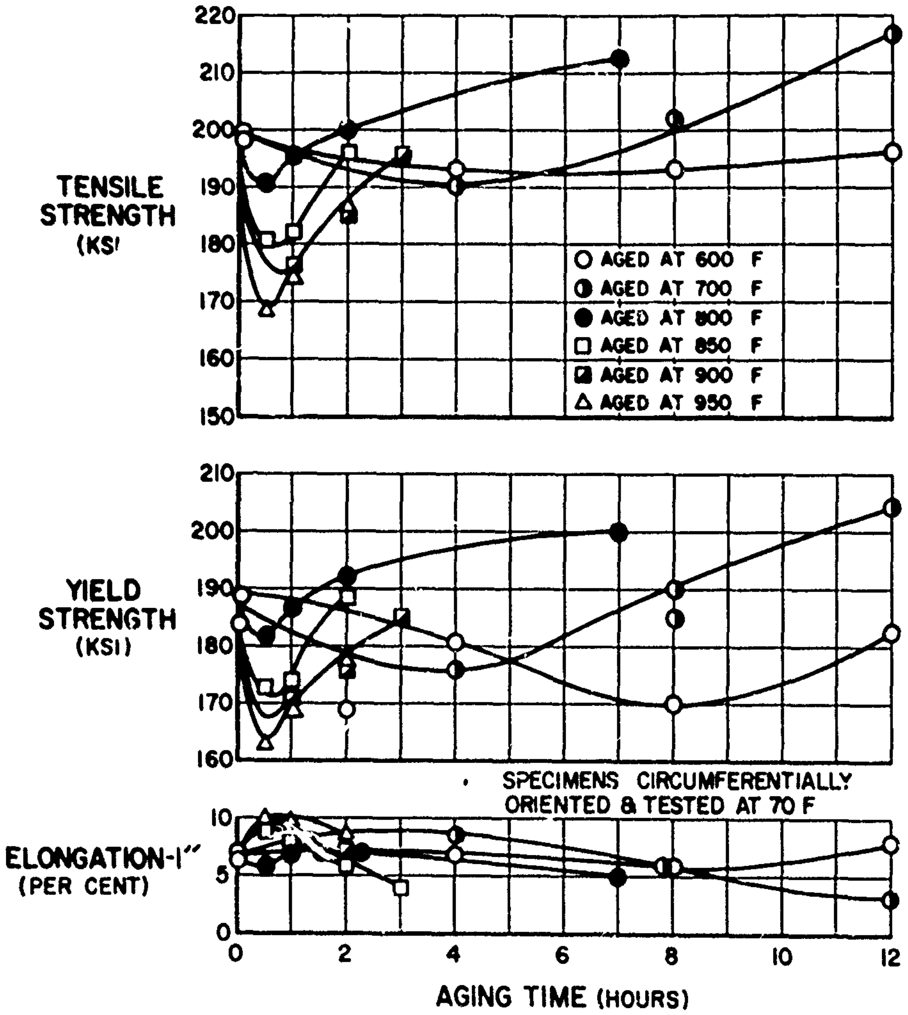


Figure 42

AGING RESPONSE OF 9.4-INCH DIAMETER FLOW-TURNED CYLINDERS PREVIOUSLY STRESS-RELIEVED AT 850 TO 950 F FOR 30 MINUTES

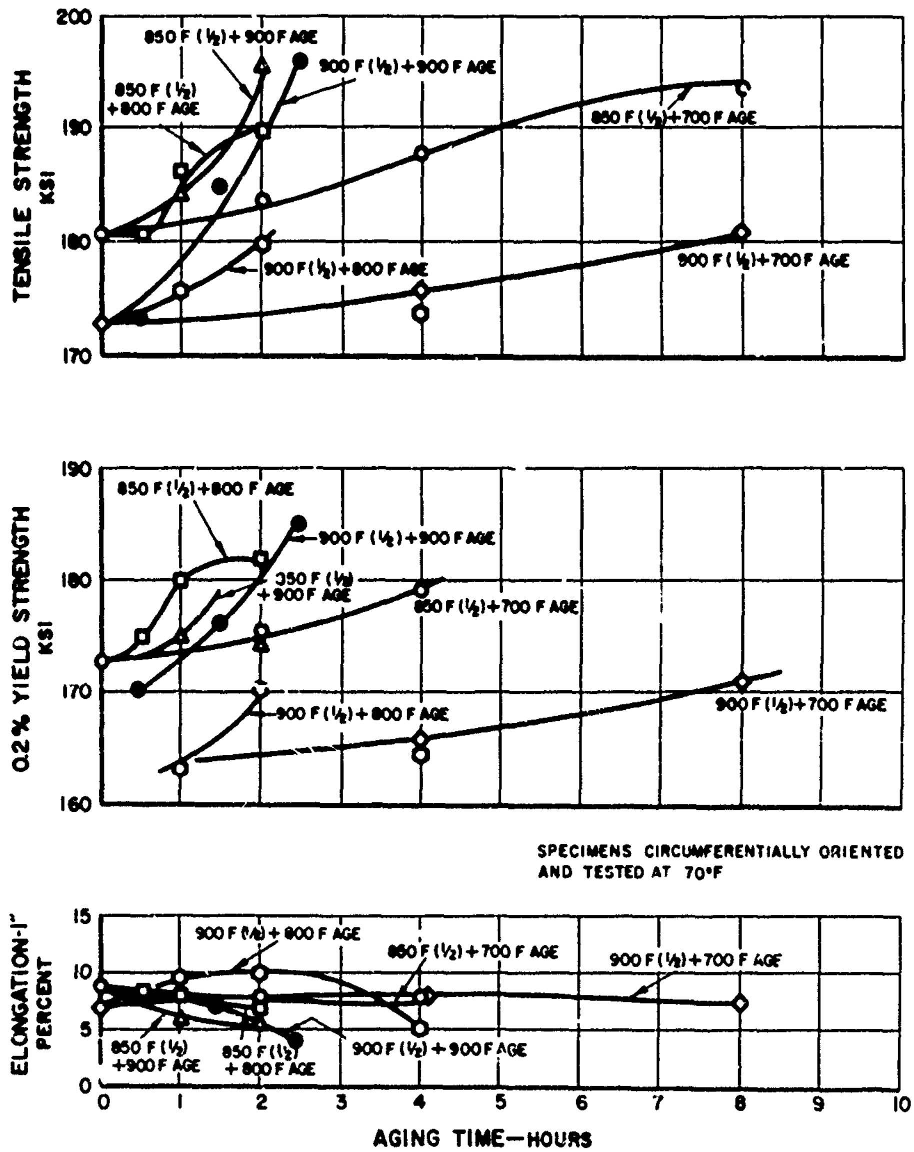


Figure 43

AGING RESPONSE OF 9.4-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDERS STRESS RELIEVED AT 850 TO 950F FOR ONE HOUR

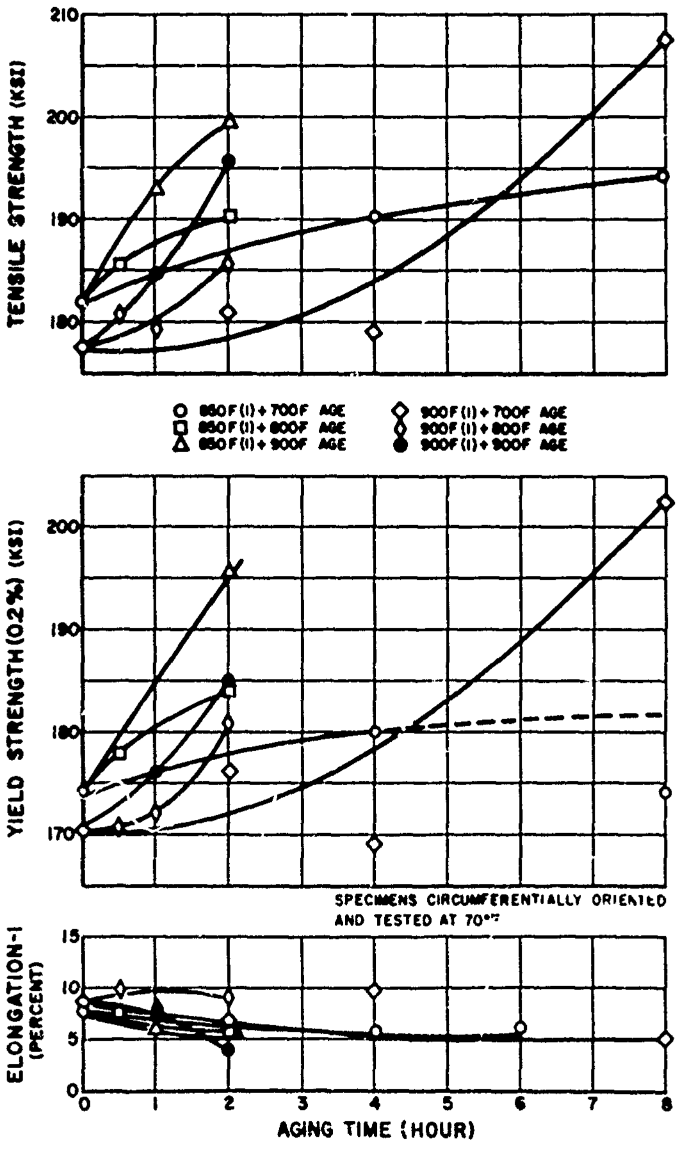


Figure 44

STRESS-RELIEF OF 9.4-INCH AND 40-INCH DIAMETER FLOW-TURNED CYLINDERS AS A FUNCTION OF HEAT TREATMENT

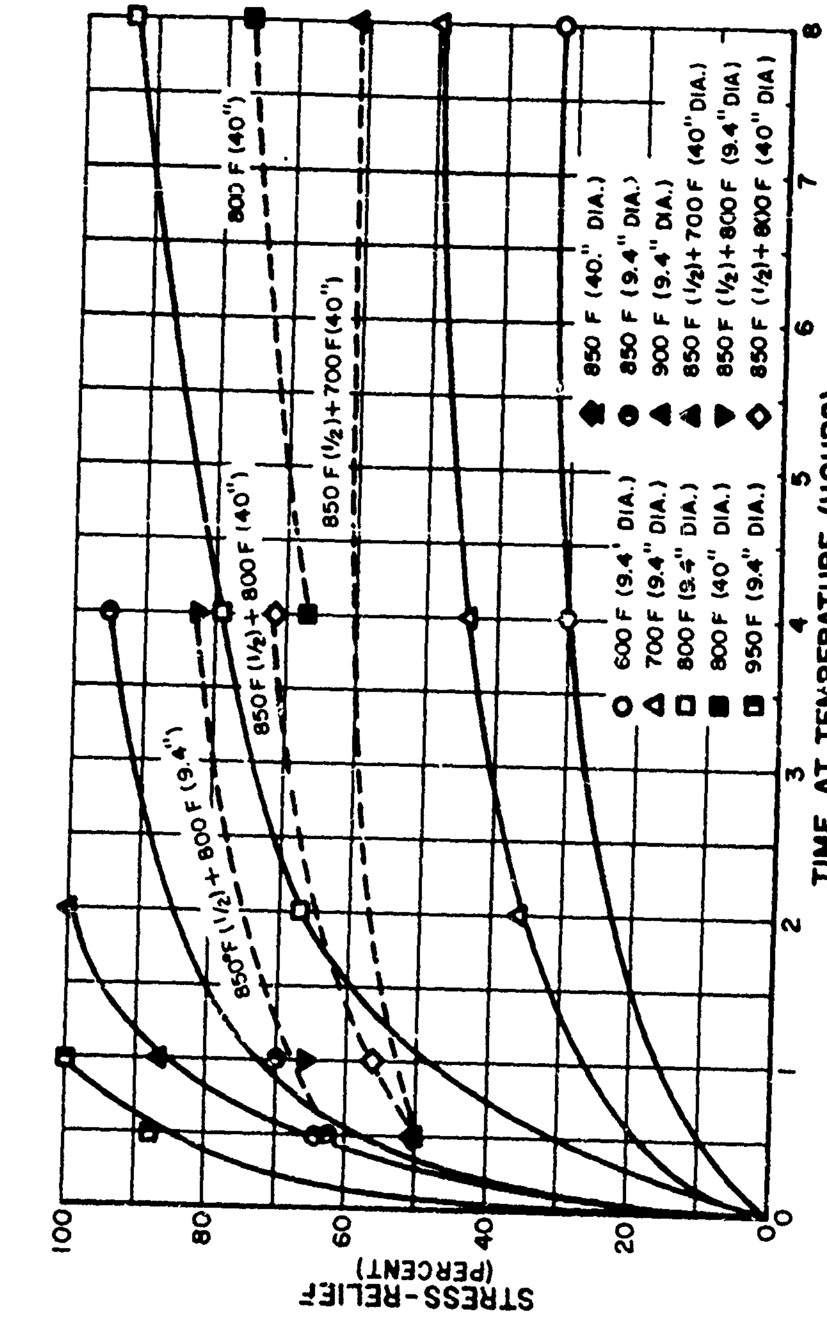


Figure 45

AGING RESPONSE OF 9.4-INCH DIAMETER FLOW-TURNED B-120 VCA TITANIUM ALLOY CYLINDER ANNEALED AT 1400 F FOR 30 MINUTES AND AGED AT 800 AND 900 F

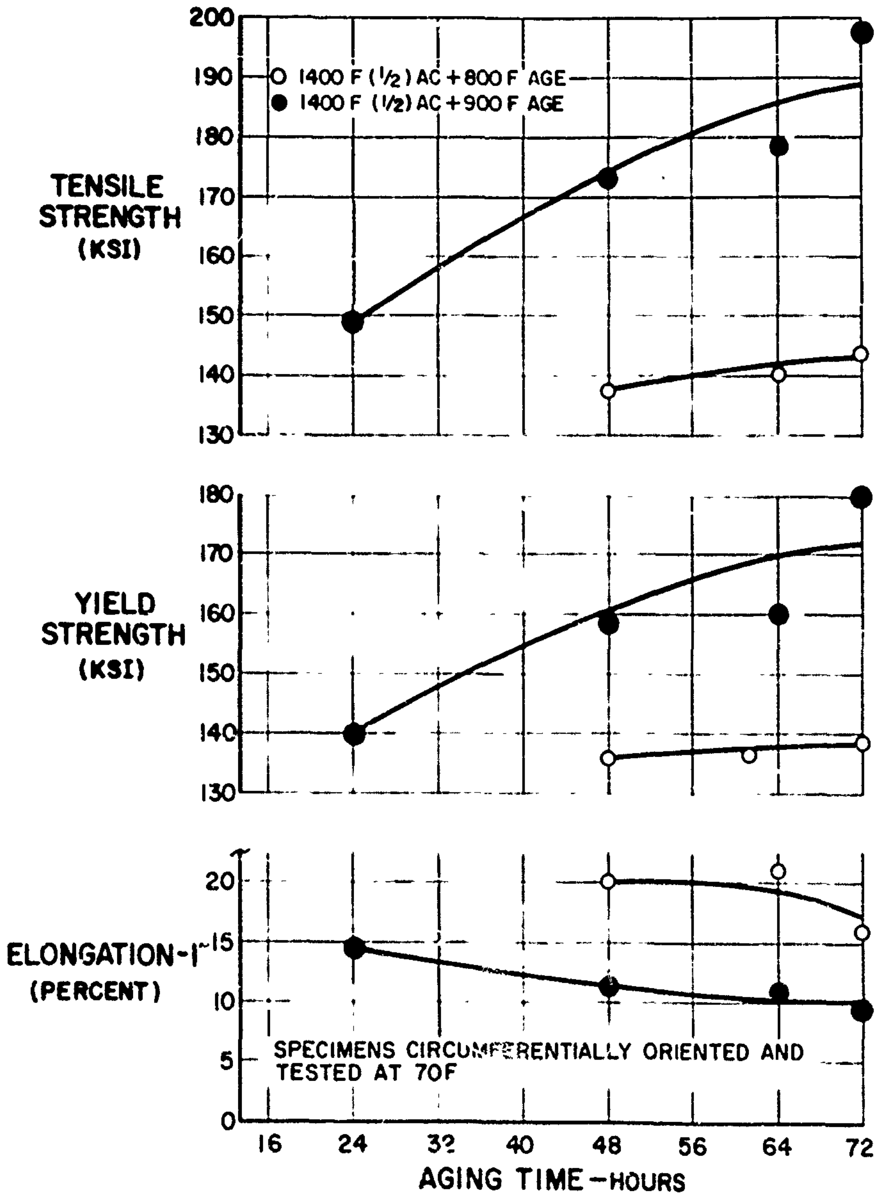


Figure 46

AGING RESPONSE OF 9.4-INCH DIAMETER FLOW-TURNED B-120 VCA TITANIUM ALLOY CYLINDER ANNEALED AT 1450 F FOR 15 MINUTES AND AGED AT 800 AND 900 F

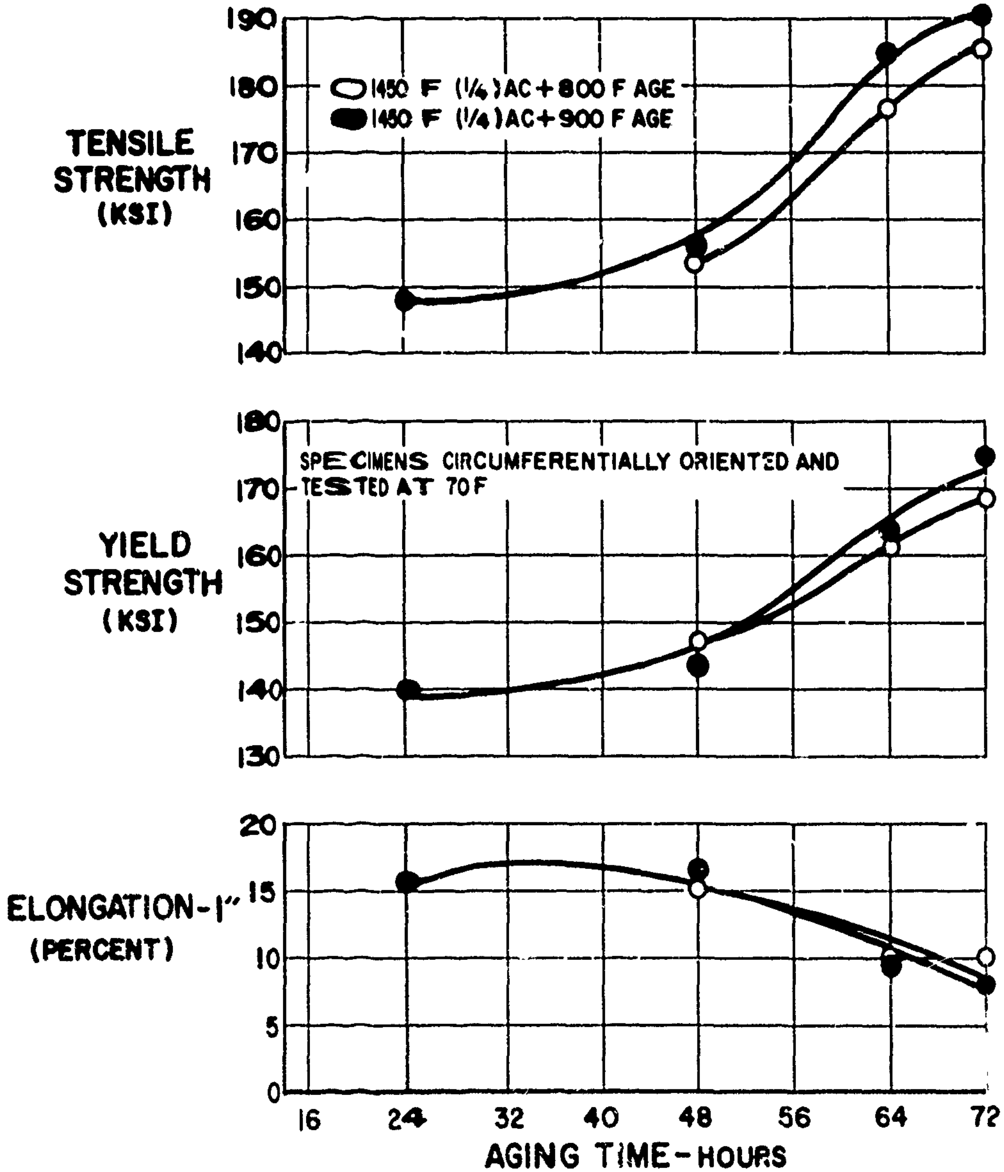


Figure 47

AGING RESPONSE OF 9.4 INCH DIAMETER FLOW-TURNED B-120 VCA TITANIUM ALLOY CYLINDER ANNEALED AT 1500F FOR 5 MINUTES AND AGED AT 800 AND 900 F

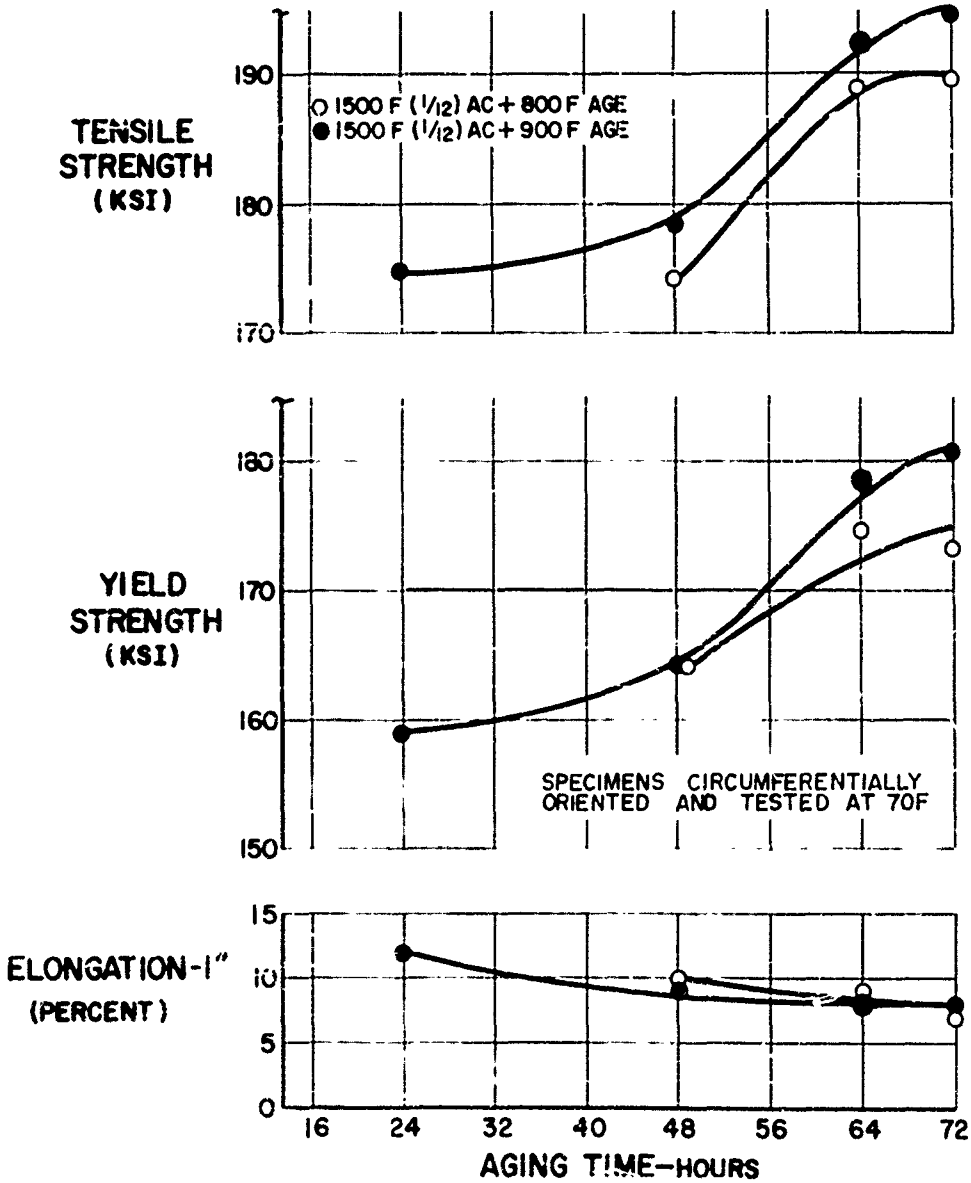


Figure 48

AGING RESPONSE OF 14-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDER NUMBER 1 STRESS RELIEVED AT 900F FOR ONE HOUR

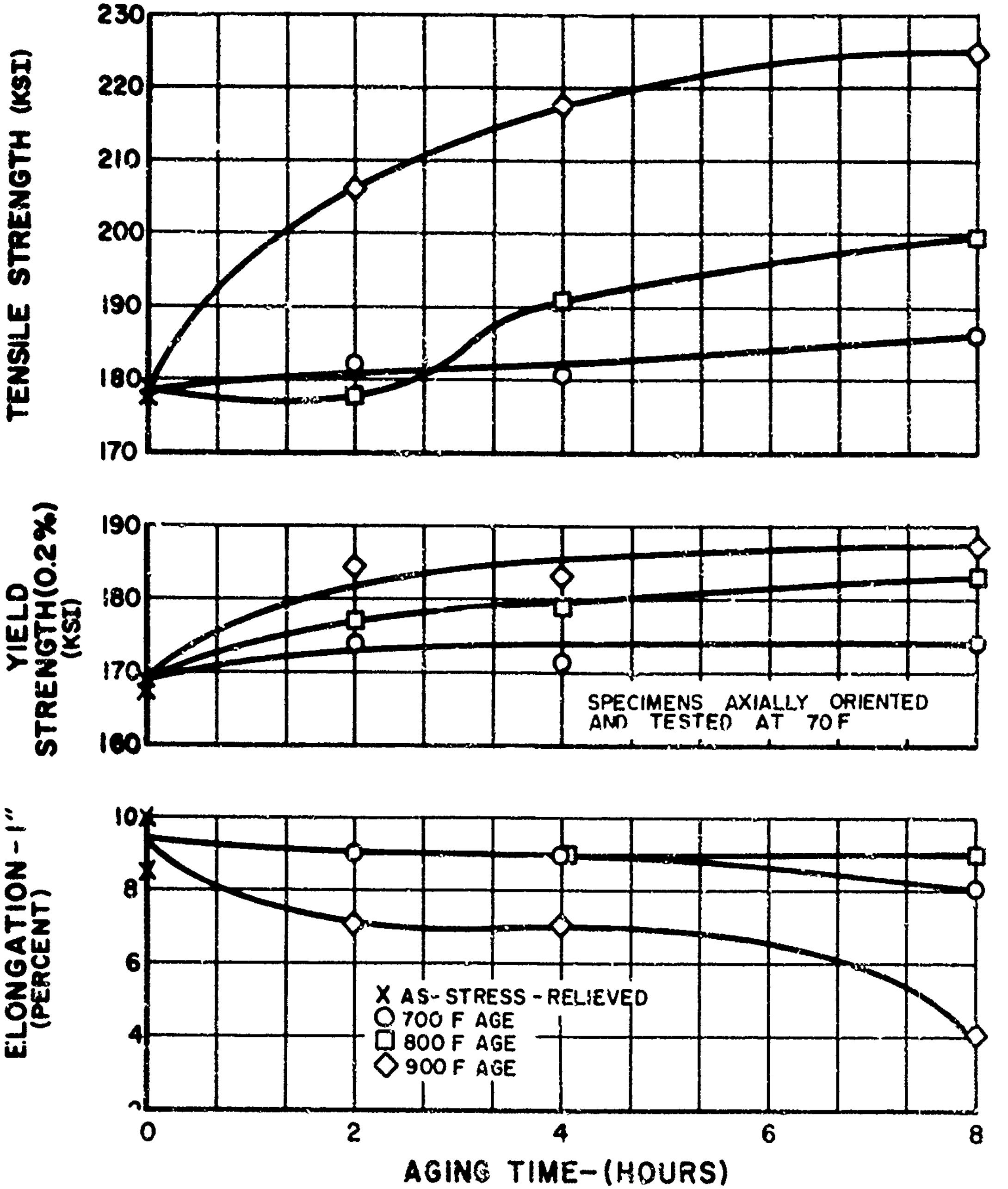


Figure 49

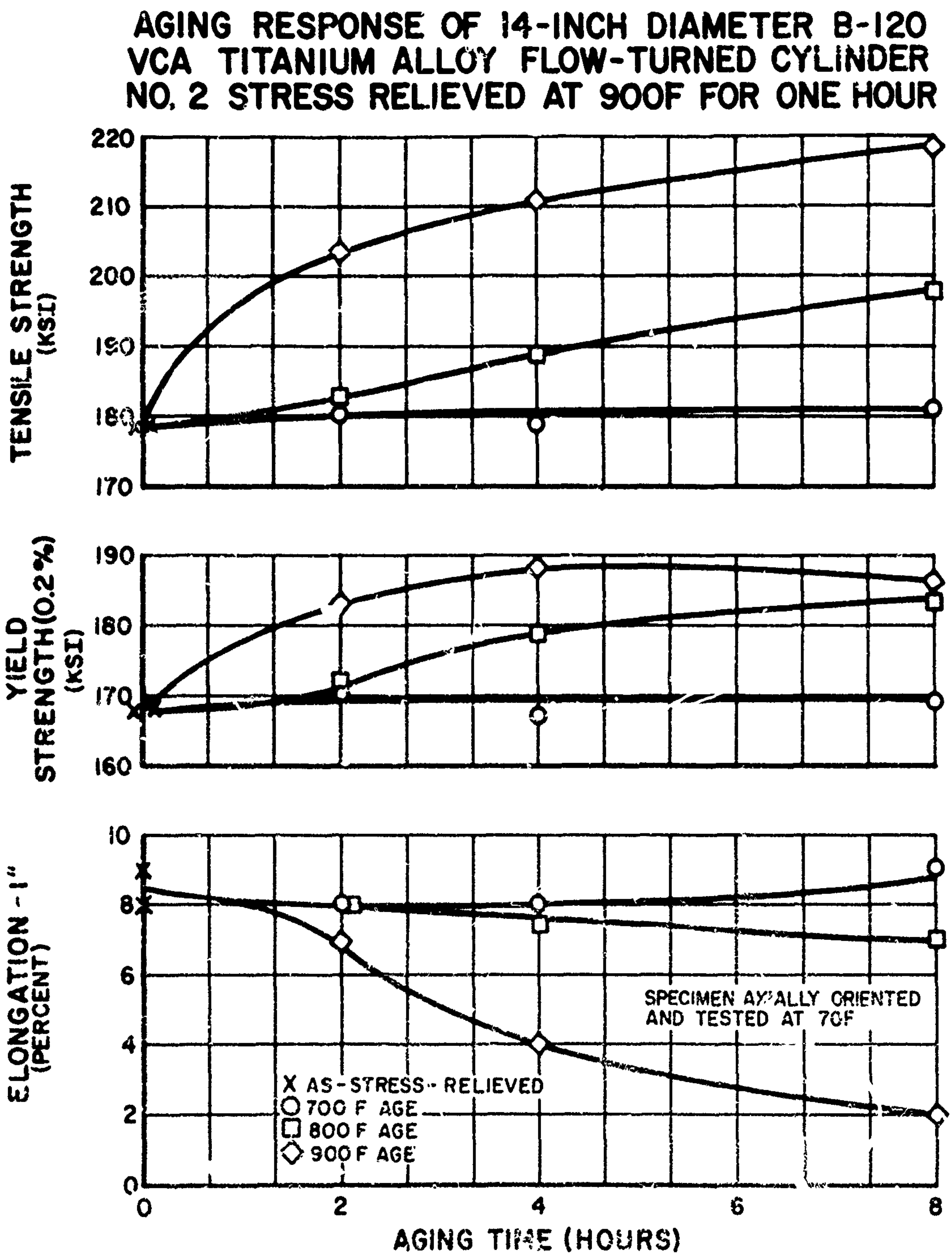

AGING RESPONSE OF 14-INCH DIAMETER B-120
VCA TITANIUM ALLOY FLOW-TURNED CYLINDER
NO. 2 STRESS RELIEVED AT 900F FOR ONE HOUR
TENSILE STRENGTH (KSI)
220
210
200
190
180
170
YIELD STRENGTH (0.2%) (KSI)
190
180
170
160
ELONGATION - 1" (PERCENT)
10
8
6
4
2
0
SPECIMEN AXIALLY ORIENTED AND TESTED AT 70F
X AS-STRESS-RELIEVED
700 F AGE
800 F AGE
900 F AGE
0
2
4
6
8
AGING TIME (HOURS)

Figure 50

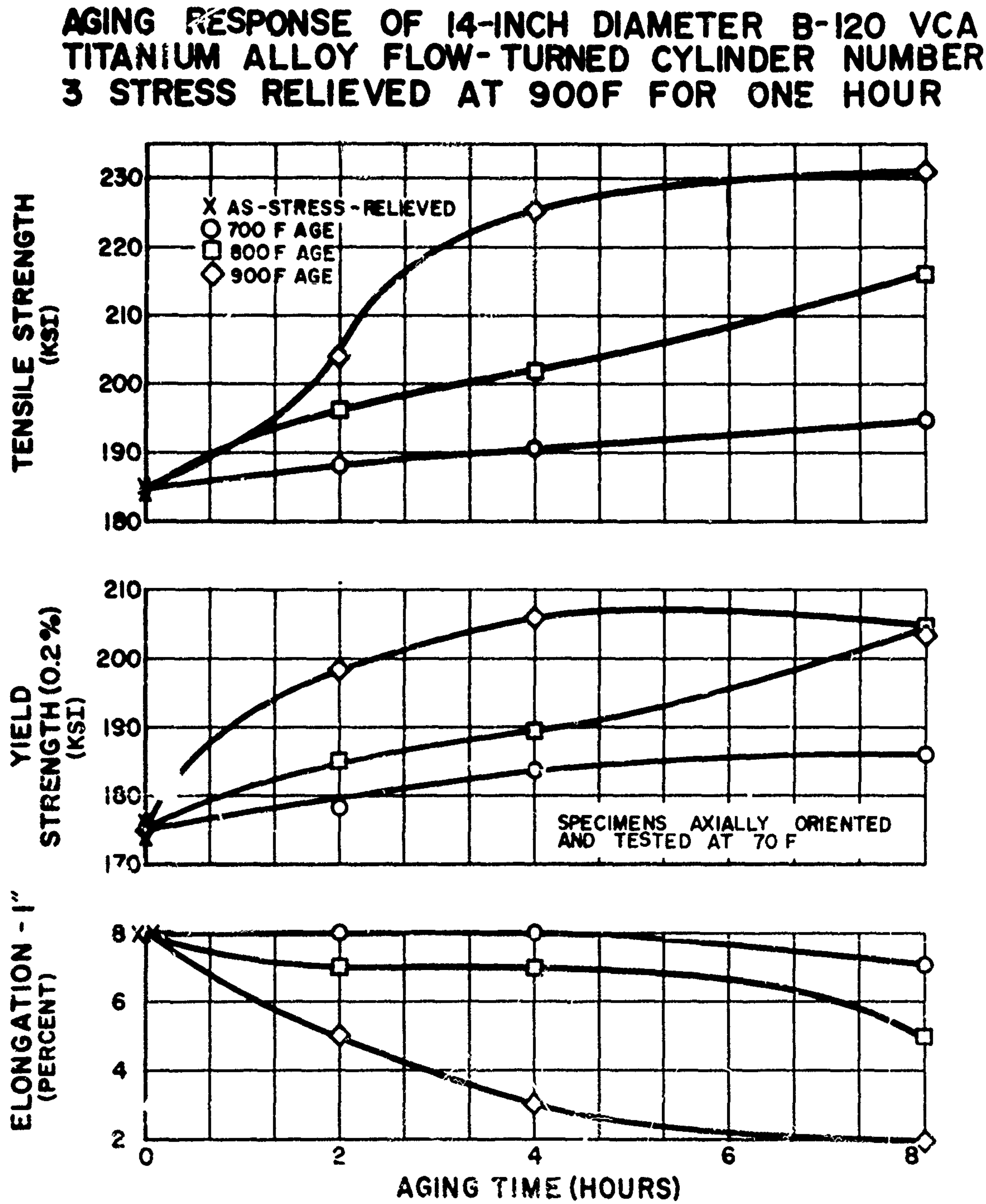

AGING RESPONSE OF 14-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDER NUMBER 3 STRESS RELIEVED AT 900F FOR ONE HOUR
X AS-STRESS-RELIEVED
700 F AGE
800 F AGE
900 F AGE
TENSILE STRENGTH (KSI)
YIELD STRENGTH (0.2%) (KSI)
SPECIMENS AXIALLY ORIENTED AND TESTED AT 70 F
ELONGATION - 1" (PERCENT)
AGING TIME (HOURS)
230
220
210
200
190
180
170
8
6
4
2
0
2
4
6
8

Figure 51

AGING RESPONSE OF 14-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDERS NO. 1, 2 AND 3 STRESS RELIEVED AT 900F FOR ONE HOUR

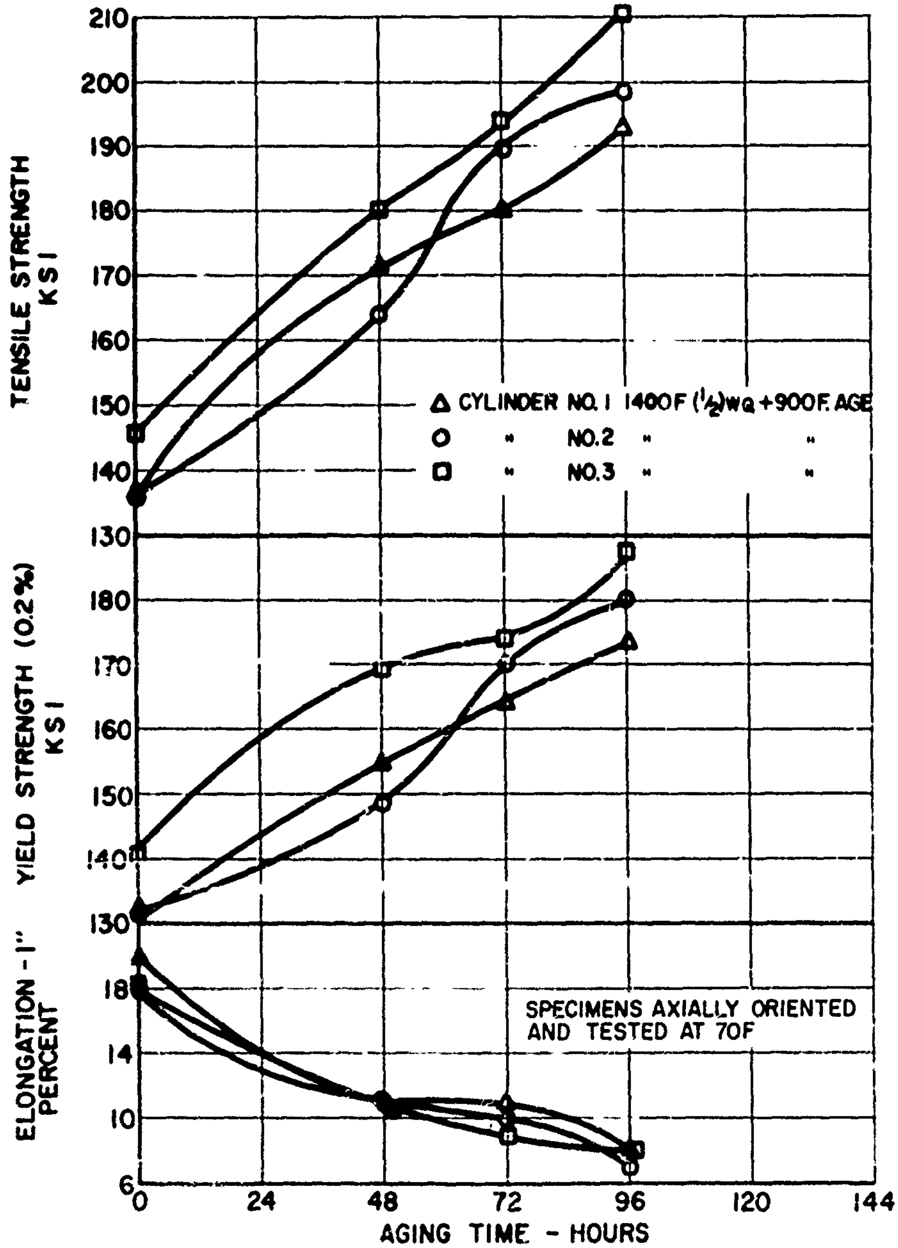


Figure 52

AGING RESPONSE OF 14-INCH DIAMETER FLOW-TURNED CYLINDER NO. 4 STRESS RELIEVED AT 850F FOR 30 MINUTES

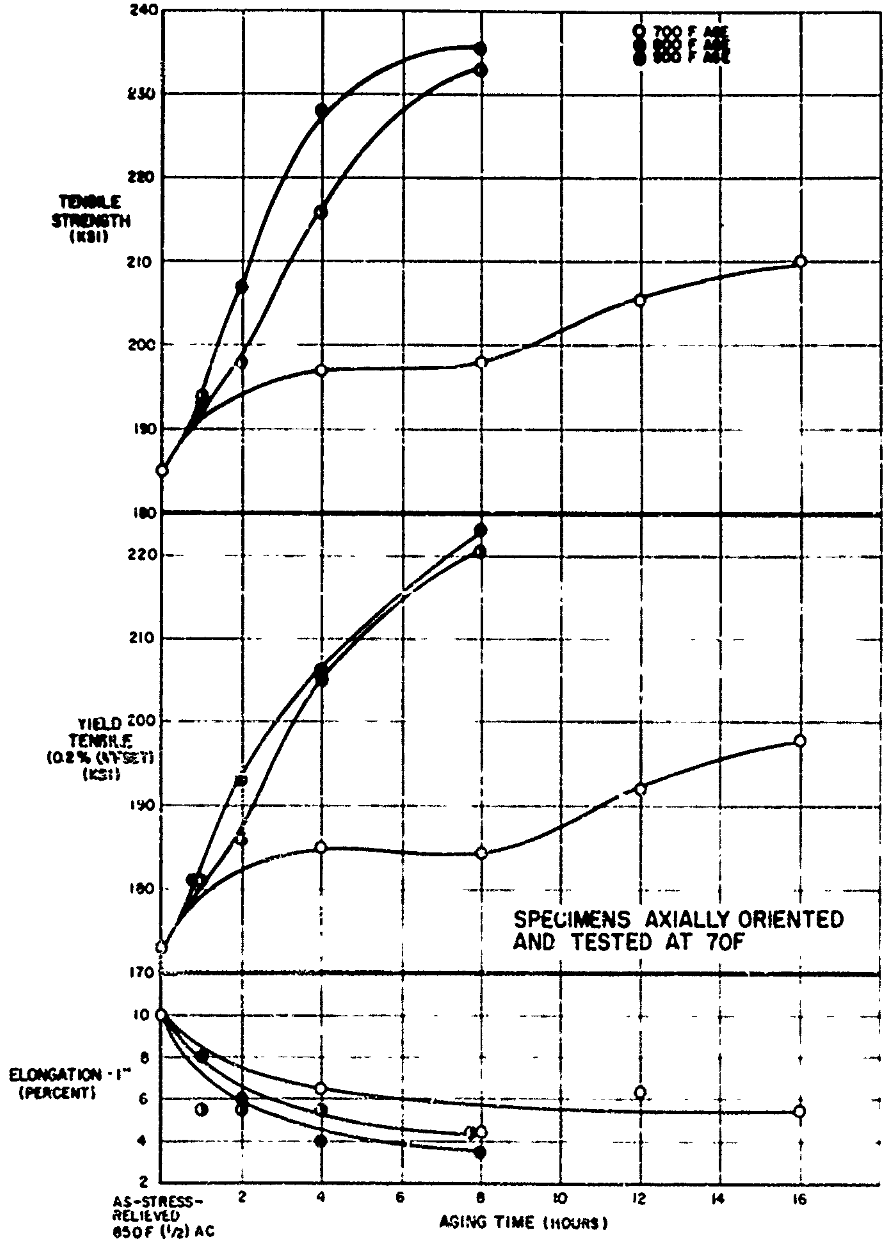


Figure 53

AGING RESPONSE OF 14-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDER NUMBER 4 STRESS RELIEVED AT 850F FOR ONE HOUR

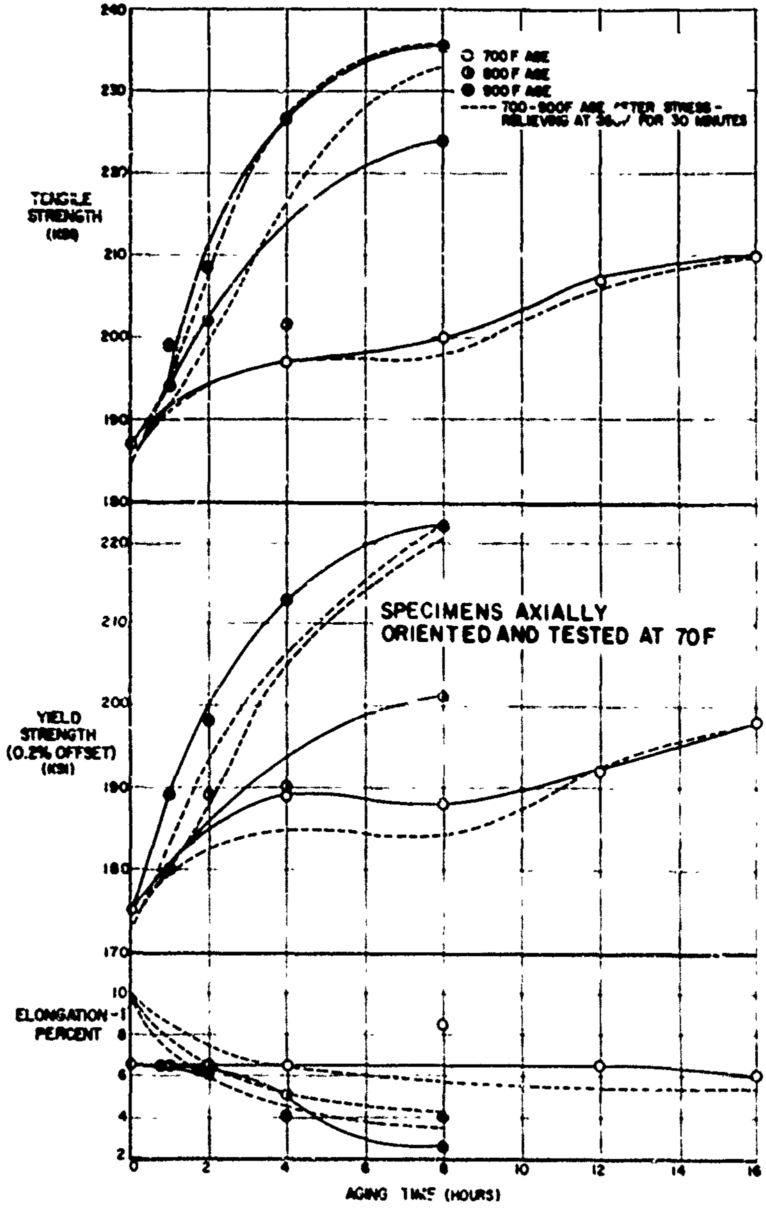


Figure 54

AGING RESPONSE OF 14-INCH DIAMETER B-120 VCA TITANIUM ALLOY FLOW-TURNED CYLINDER NUMBER 4 STRESS RELIEVED AT 900 F FOR ONE HOUR

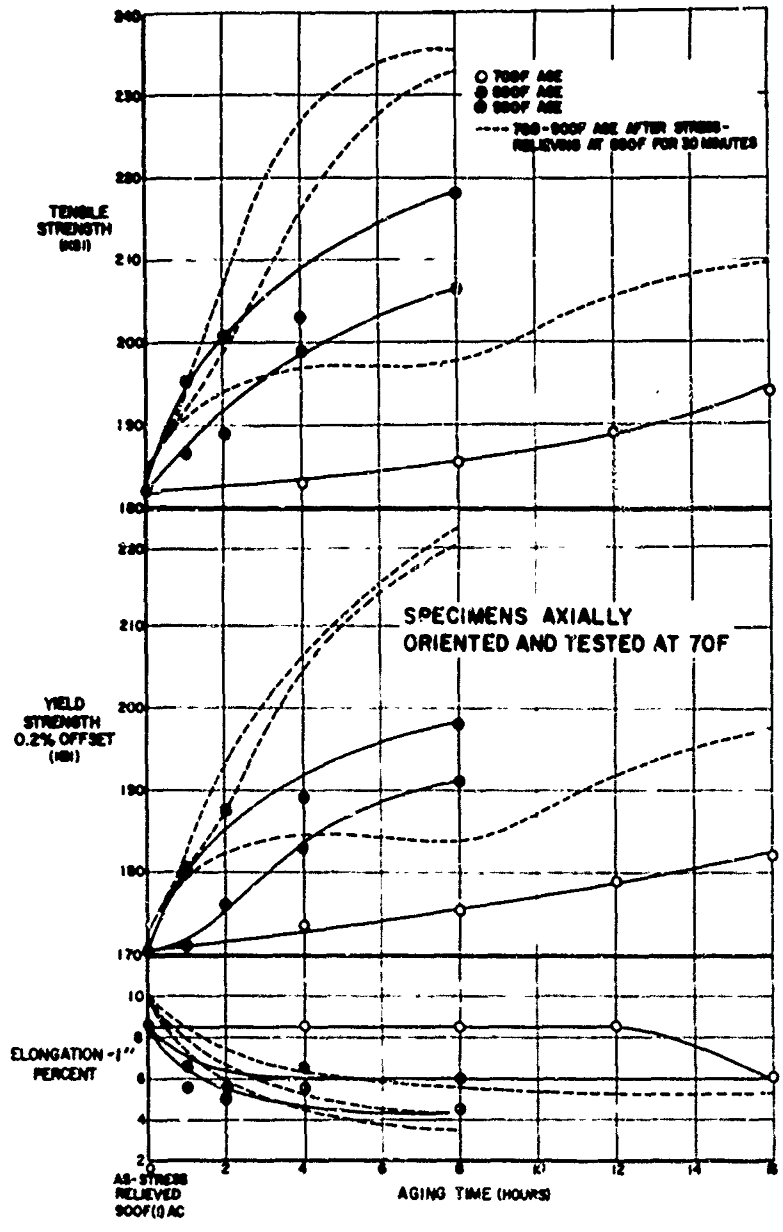


Figure 55

AGING RESPONSE OF 14-INCH DIAMETER CYLINDER NUMBER 7 SOLUTION TREATED AT 1800F, FLOW-TURNED AND STRESS RELIEVED AT 850F FOR 1/2 HR

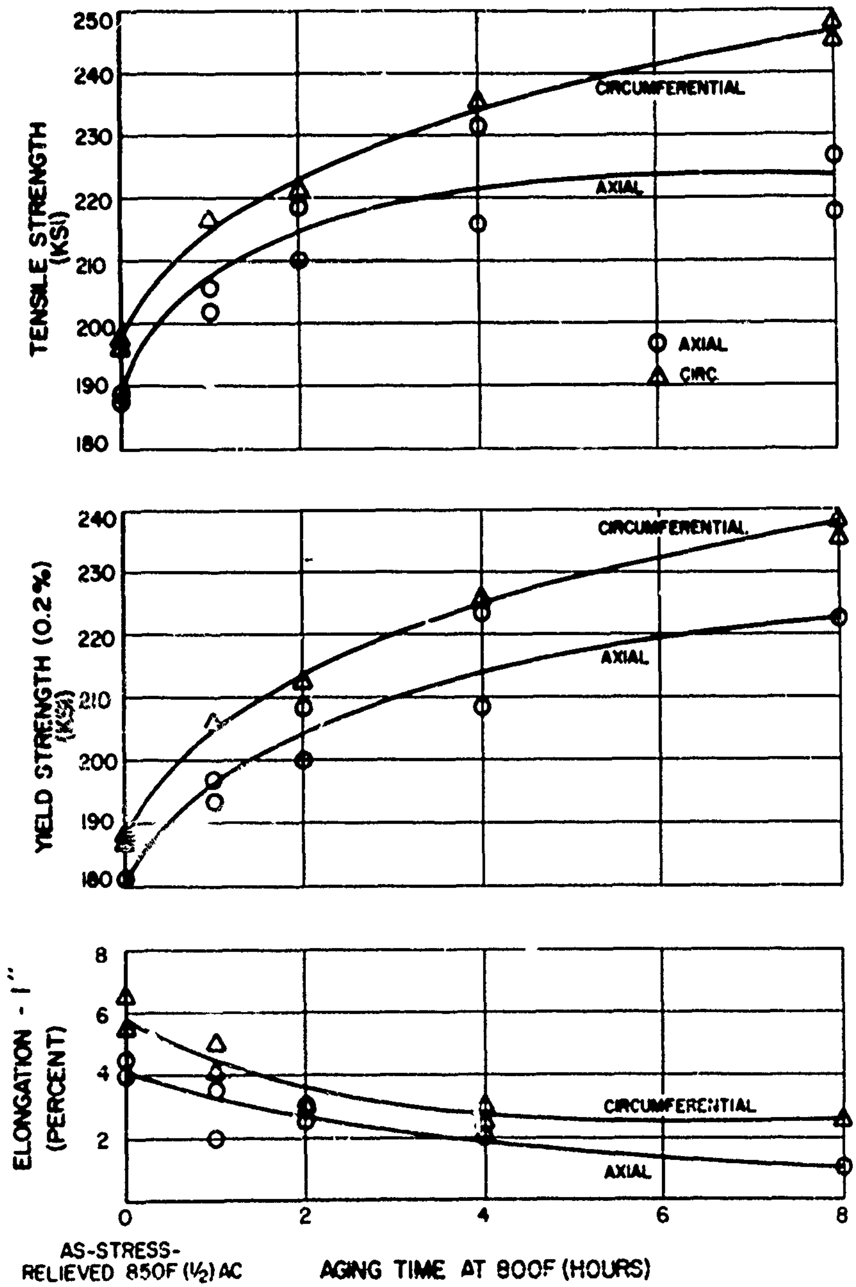


Figure 56

AGING RESPONSE OF 14-INCH DIA FLOW-TURNED CYLINDER NO. 8 STRESS-RELIEVED (850 F (1/2) AC) AND AGED AT 800 F

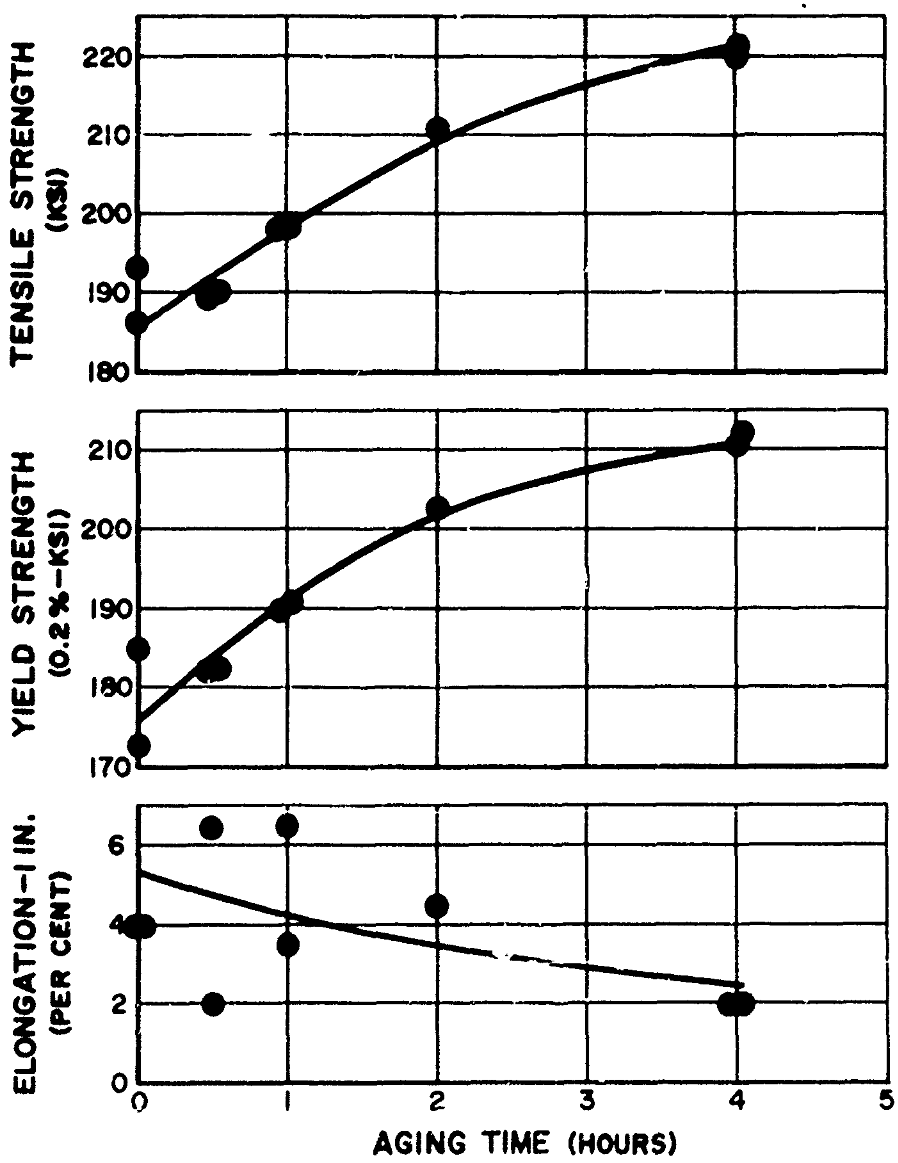


Figure 57

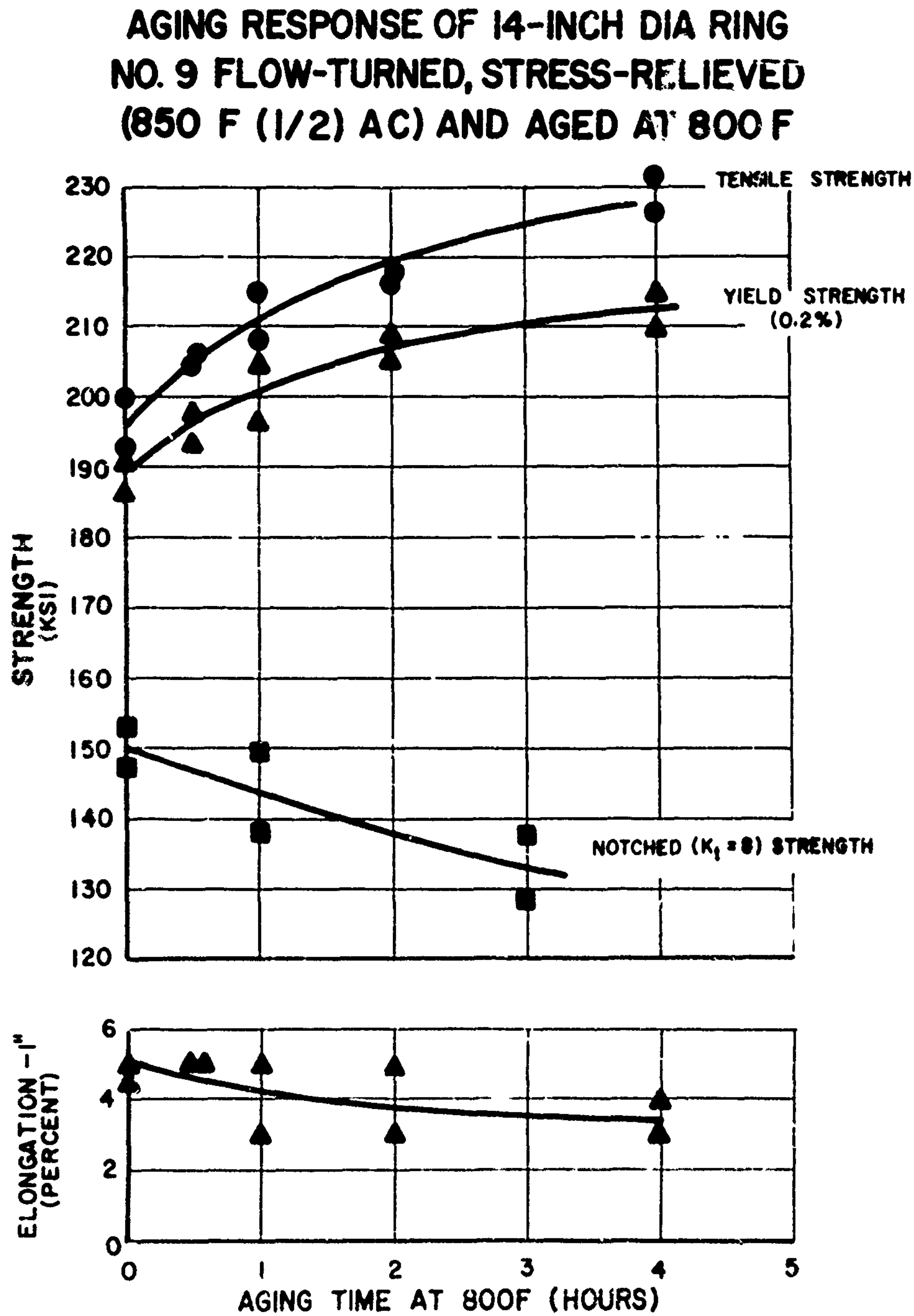

AGING RESPONSE OF 14-INCH DIA RING
NO. 9 FLOW-TURNED, STRESS-RELIEVED
(850 F (1/2) AC) AND AGED AT 800 F
TENSILE STRENGTH
YIELD STRENGTH
(0.2%)
NOTCHED (K_t = 8) STRENGTH
STRENGTH
(KSI)
230
220
210
200
190
180
170
160
150
140
130
120
ELONGATION - 1"
(PERCENT)
6
4
2
0
0
1
2
3
4
5
AGING TIME AT 800F (HOURS)

Figure 58

AGING RESPONSE OF 14-INCH DIA RING NO. 10 FLOW-TURNED, STRESS-RELIEVED (850 F (1/2) AC) AND AGED AT 800 F

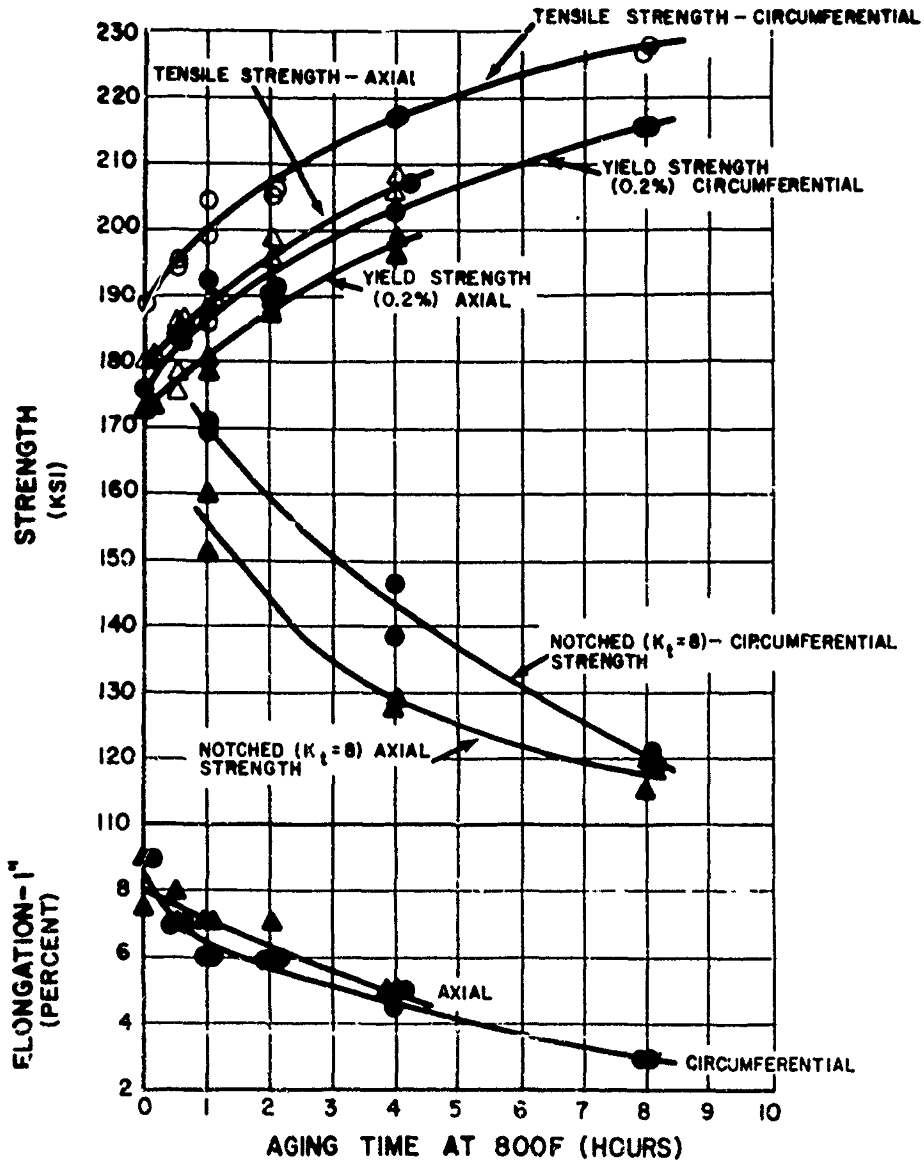


Figure 59

FRACTURE TOUGHNESS (G_c^*) vs YIELD STRENGTH FOR FLOW-TURNED (50% REDUCTION EACH PASS) AND AGED B-120 VCA TITANIUM ALLOY 0.075 INCH THICK

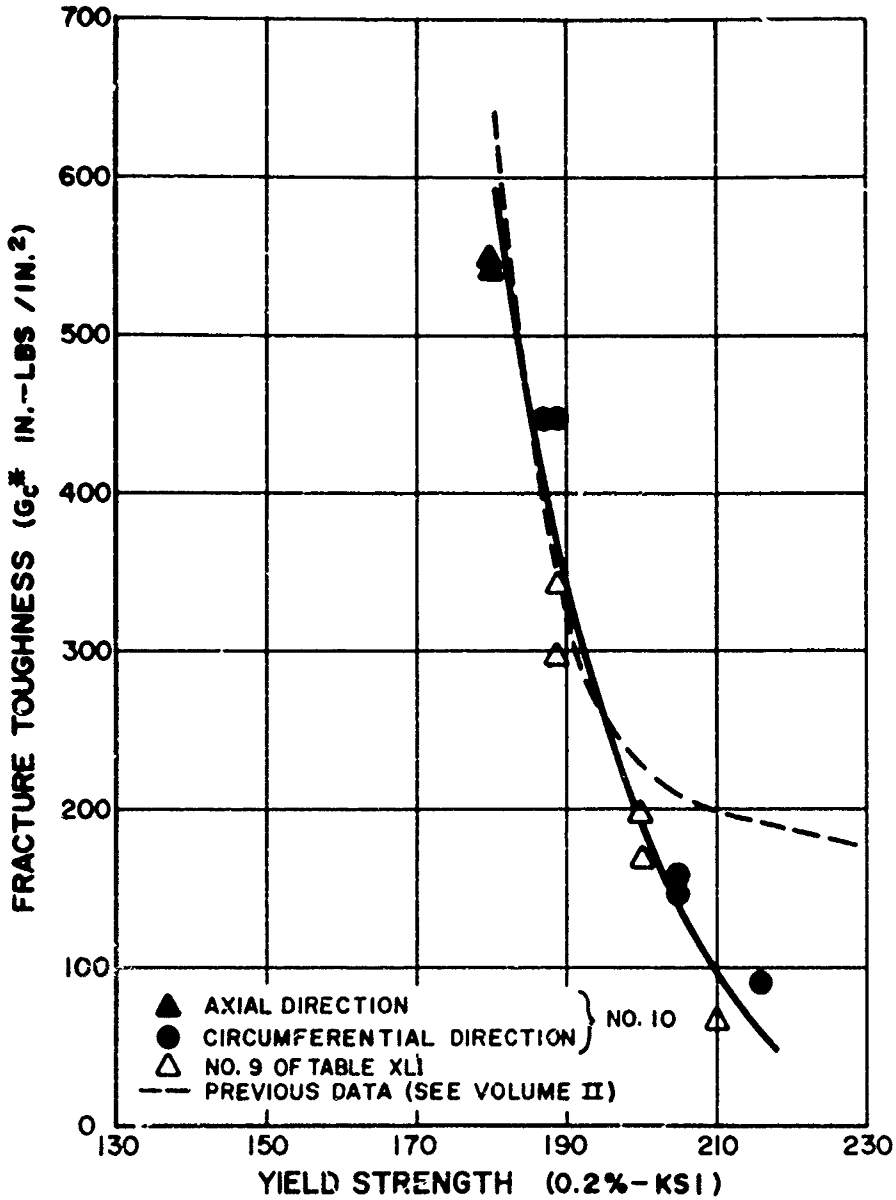


Figure 60

RELATIONSHIP OF AMOUNT OF HYDROGEN INTRODUCED TO PROCESSING TIME FOR CATHODIC HYDROGENATION OF COLD-ROLLED SHEET STOCK

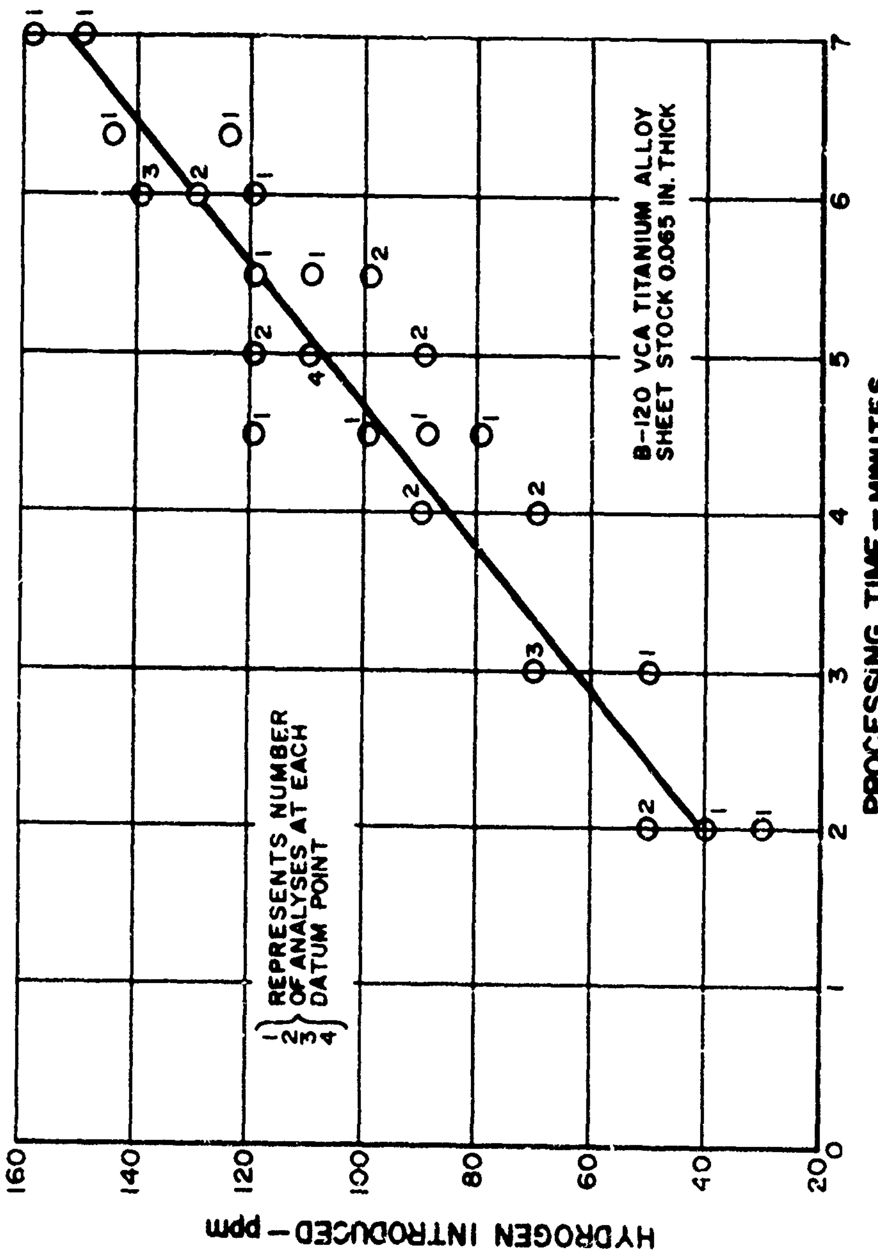


Figure 61

SMOOTH AND NOTCHED (K_t = 8) TENSILE PROPERTIES VS TEST TEMPERATURE FOR COLD-ROLLED (50% REDUCTION) AND AGED SHEET STOCK WITH HYDROGEN CONTENTS OF 70 AND 200 PPM

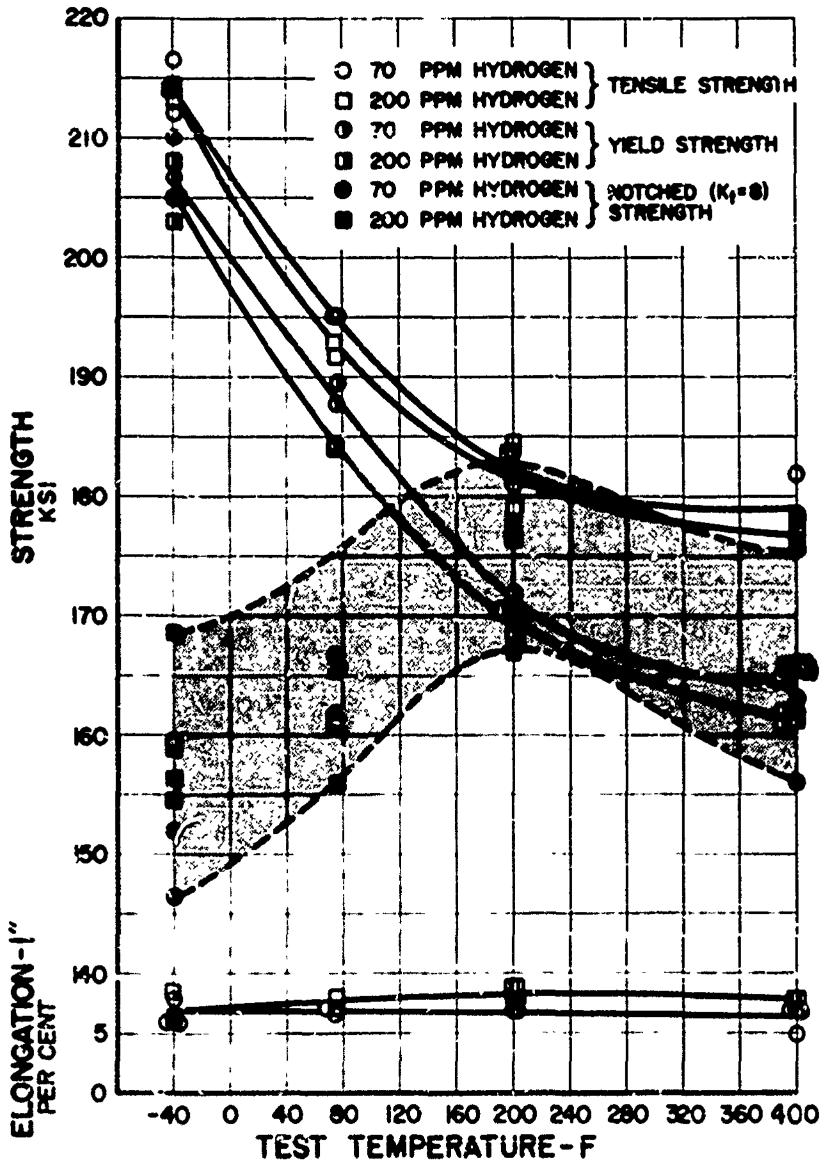


Figure 62

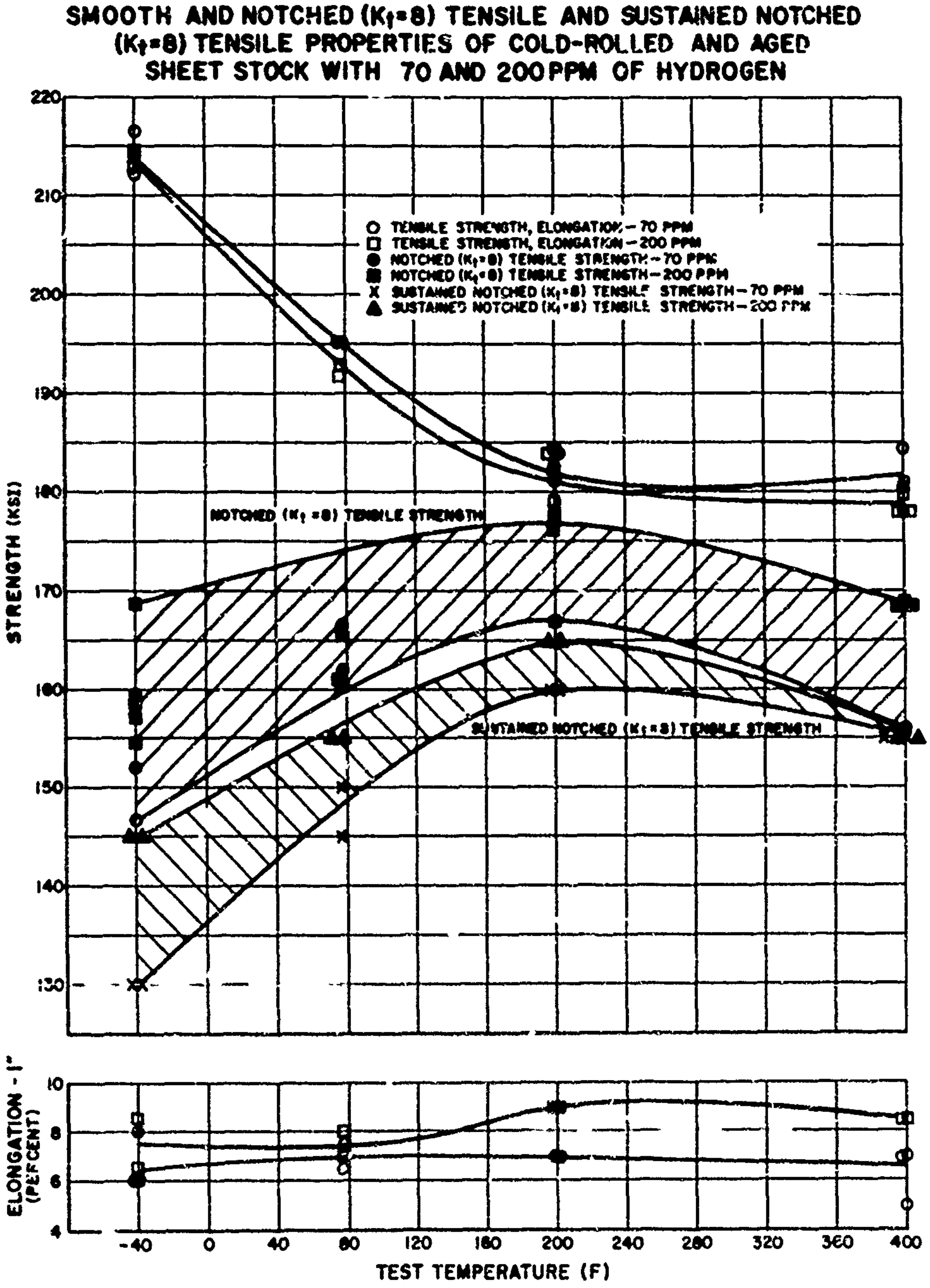

SMOOTH AND NOTCHED (Kt=8) TENSILE AND SUSTAINED NOTCHED (Kt=8) TENSILE PROPERTIES OF COLD-ROLLED AND AGED SHEET STOCK WITH 70 AND 200 PPM OF HYDROGEN
TENSILE STRENGTH, ELONGATION - 70 PPM
TENSILE STRENGTH, ELONGATION - 200 PPM
NOTCHED (Kt=8) TENSILE STRENGTH - 70 PPM
NOTCHED (Kt=8) TENSILE STRENGTH - 200 PPM
SUSTAINED NOTCHED (Kt=8) TENSILE STRENGTH - 70 PPM
SUSTAINED NOTCHED (Kt=8) TENSILE STRENGTH - 200 PPM
NOTCHED (Kt=8) TENSILE STRENGTH
SUSTAINED NOTCHED (Kt=8) TENSILE STRENGTH
STRENGTH (KSI)
220
210
200
190
180
170
160
150
140
130
ELONGATION - 1" (PERCENT)
10
8
6
4
-40
0
40
80
120
160
200
240
280
320
360
400
TEST TEMPERATURE (F)

Figure 63

NOTCHED TENSILE AND SUSTAINED NOTCHED TENSILE STRENGTHS OF COLD-ROLLED AND AGED SHEET STOCK WITH 70 AND 200 PPM OF HYDROGEN FOR VARIOUS STRESS CONCENTRATION FACTORS (K_t)

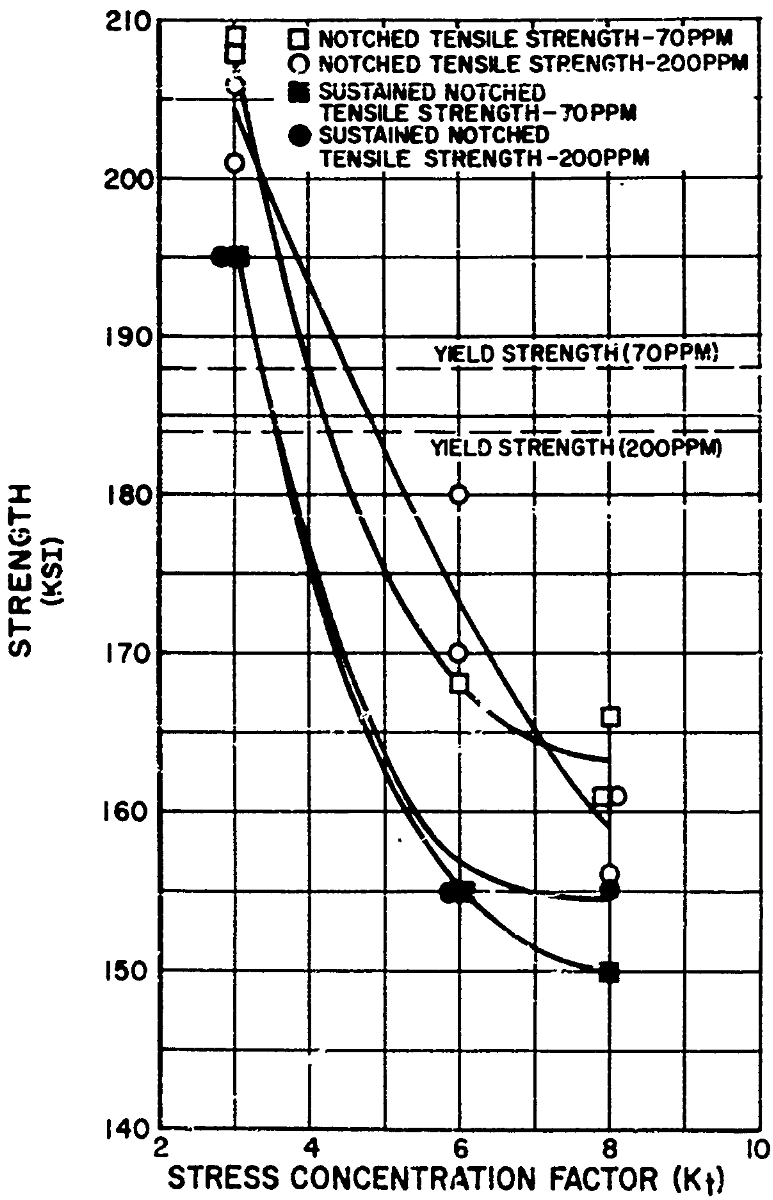


Figure 64

AXIAL TENSILE PROPERTIES vs AGING TIME (900 F) FOR FIRST SUBSCALE 14-INCH DIAMETER FLOW-TURNED CYLINDER VACUUM-ANNEALED AT 1400 F PRIOR TO FLOW-TURNING

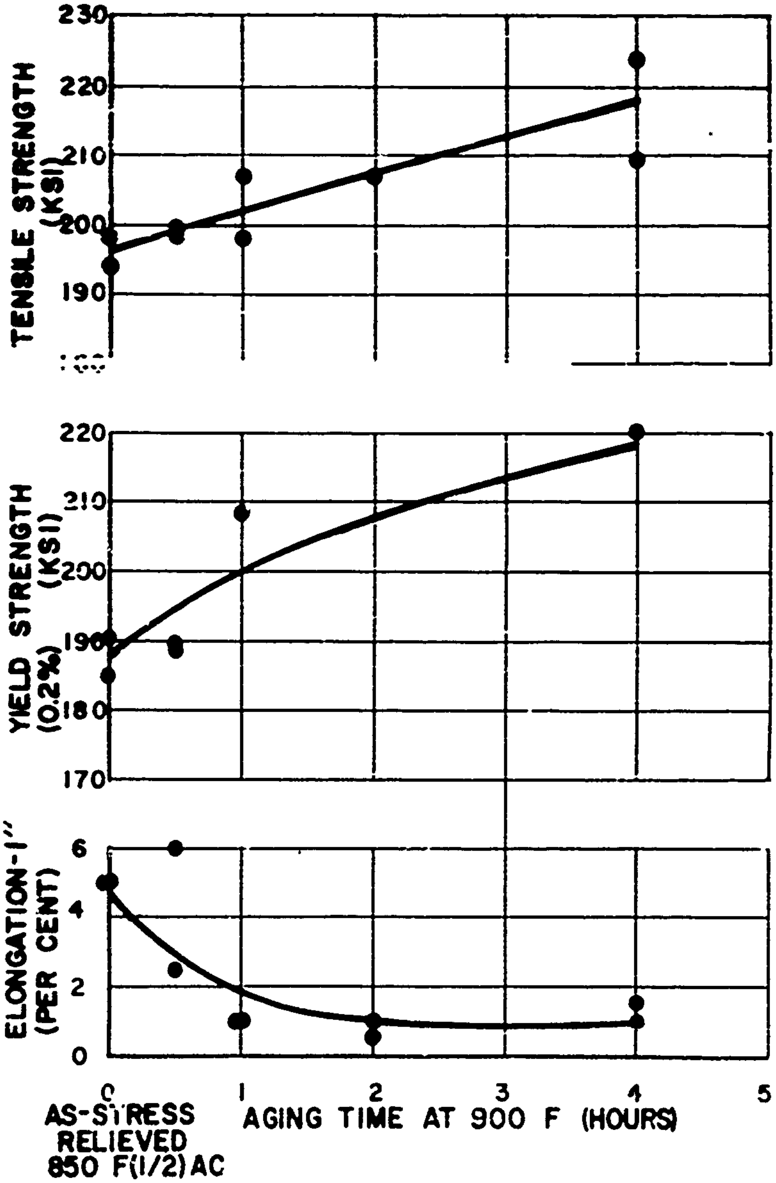


Figure 65

AXIAL TENSILE PROPERTIES VS AGING TIME FOR THE SECOND SUBSCALE 14-INCH DIAMETER CYLINDER VACUUM-ANNEALED AT 1400 F AND RE-SOLUTION-TREATED AT 1800 F PRIOR TO FLOW-TURNING

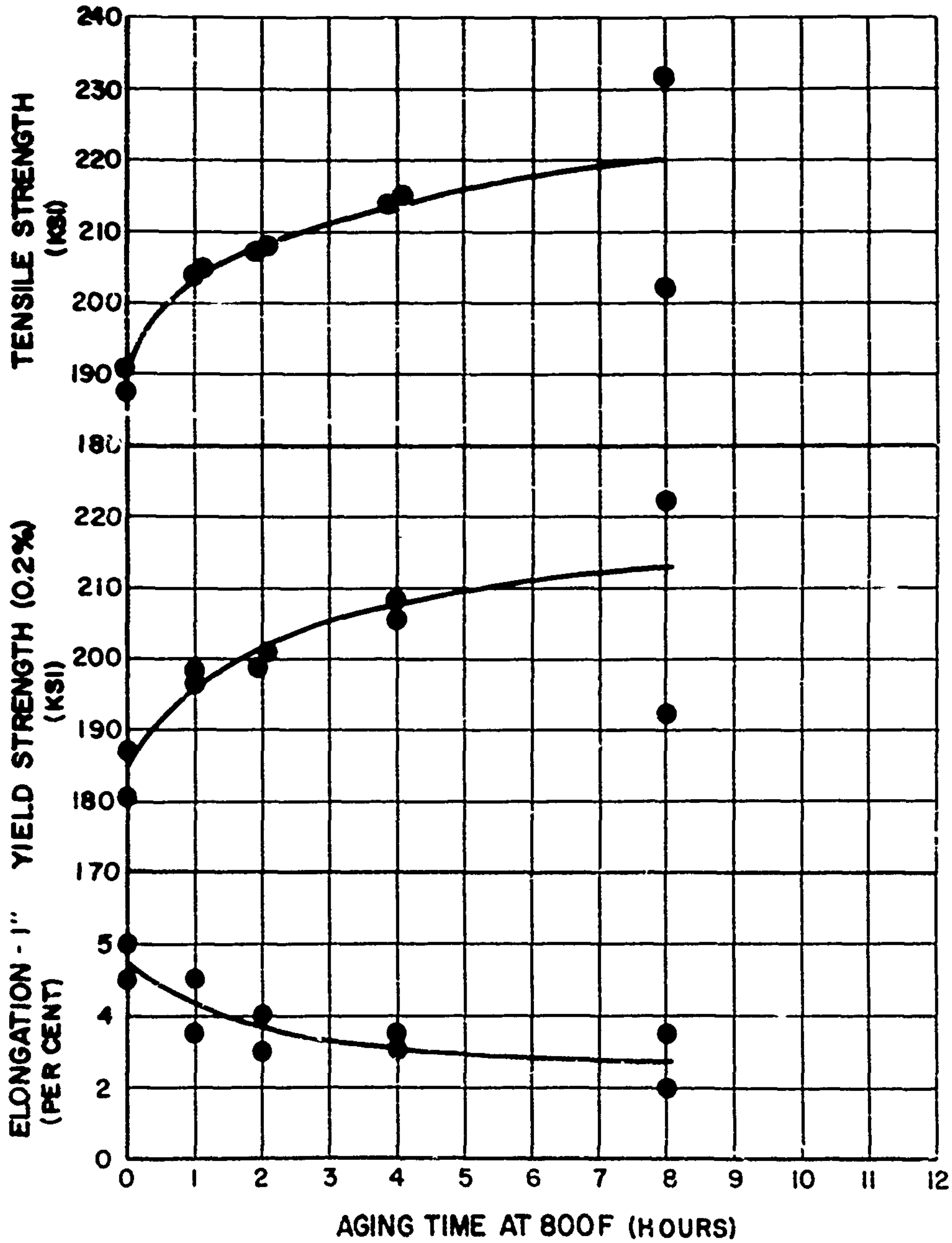


Figure 66

SMOOTH AND NOTCHED (Kt = 8) TENSILE PROPERTIES VS. TEST TEMPERATURE FOR FLOW-TURNED (50% REDUCTION TO 0.070-IN THICKNESS), AND AGED 14-INCH DIAMETER CYLINDER WITH HYDROGEN CONTENTS OF 70 AND 200 PPM

DOTTED LINES REPRESENT DATA FOR COLD ROLLED (50% REDUCTION TO 0.062-IN THICKNESS), AND AGED SHEET STOCK AT THE 70 AND 200 PPM HYDROGEN LEVELS

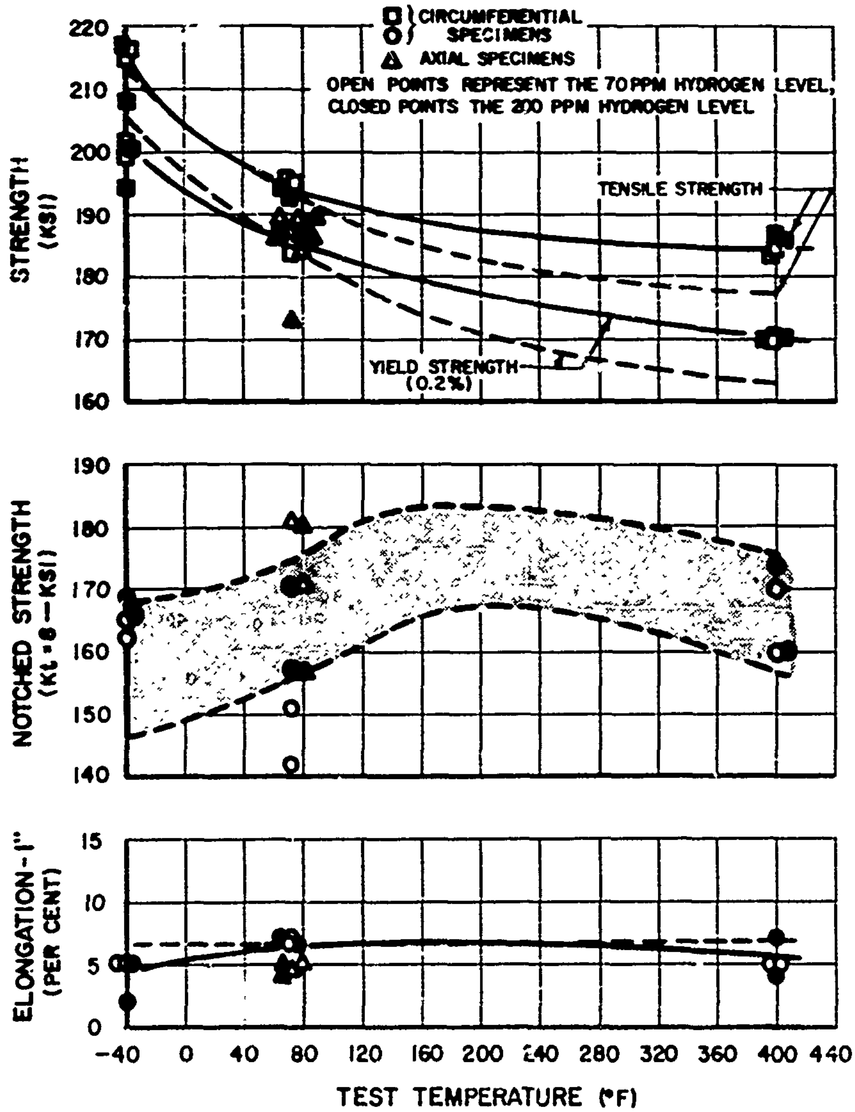
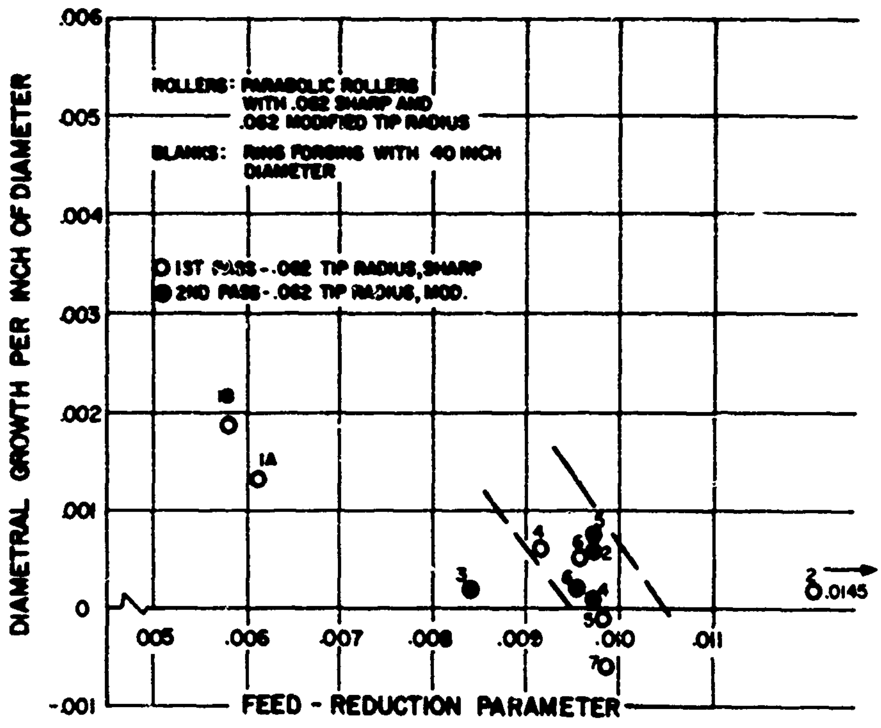


Figure 67

FLOW - TURNING RESULTS WITH PARABOLIC CONTOURS

DIAMETRAL GROWTH vs. FEED REDUCTION PARAMETER



$$\left(\frac{\text{ROLLER FEED}}{\text{MANDREL SPEED}}\right)\left(\frac{\text{PER CENT REDUCTION}}{100}\right)$$

Figure 68

Forty-Inch Diameter B-120 VCA Titanium Cylinder After Flow-Turning Preparatory to Trimming

Figure 69

TENSILE PROPERTIES OF FULL SCALE 40-INCH DIAMETER FLOW-TURNED RING F-4 STRESS RELIEVED AT 850 F (1/2) AC vs AGING TIME AT 800 F

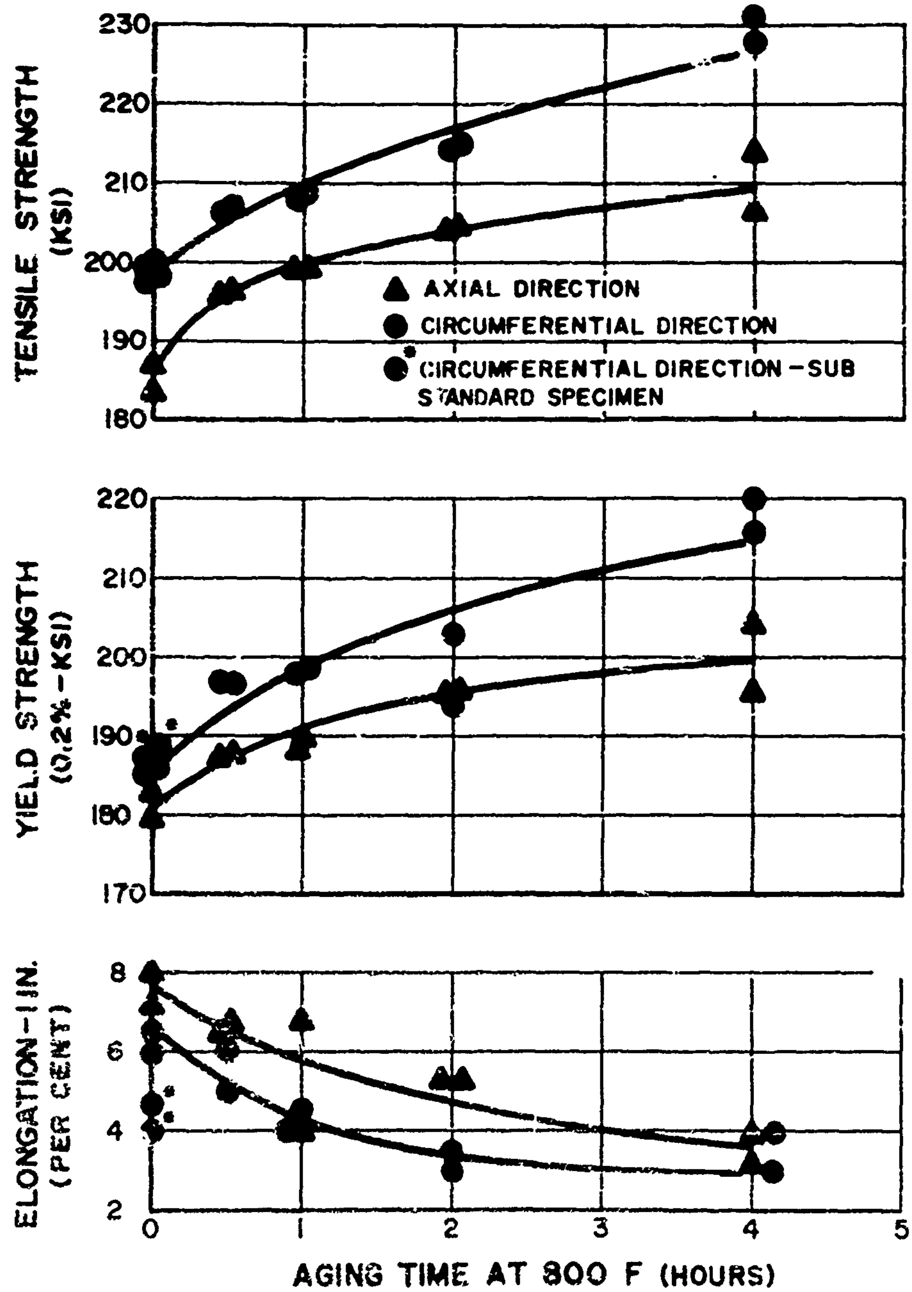


Figure 70

TENSILE PROPERTIES OF CIRCUMFERENTIAL SPECIMENS FROM 40-INCH DIAMETER FLOW-TURNED CYLINDER F-7 STRESS RELIEVED AT 850 F (1/2) AC PRESTRAINED 0.35% (AFTER MACHINING) AND AGED AT 800-850 F

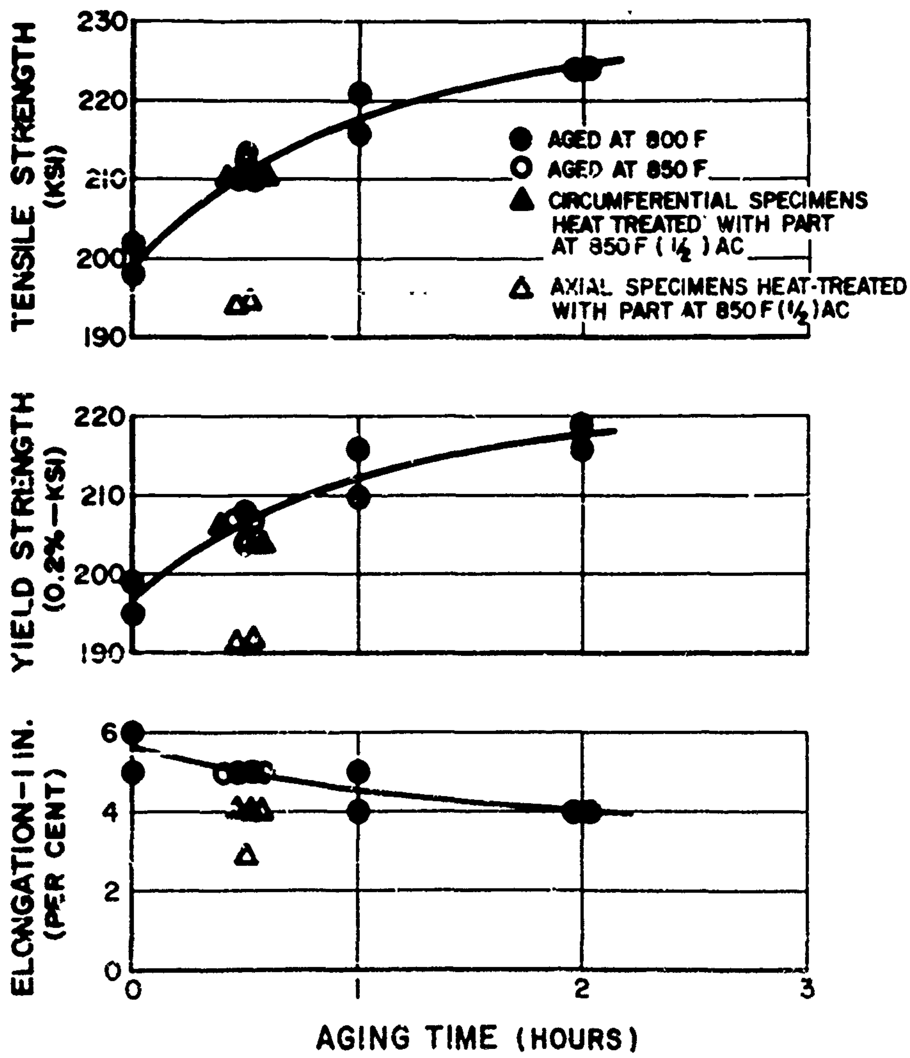


Figure 71

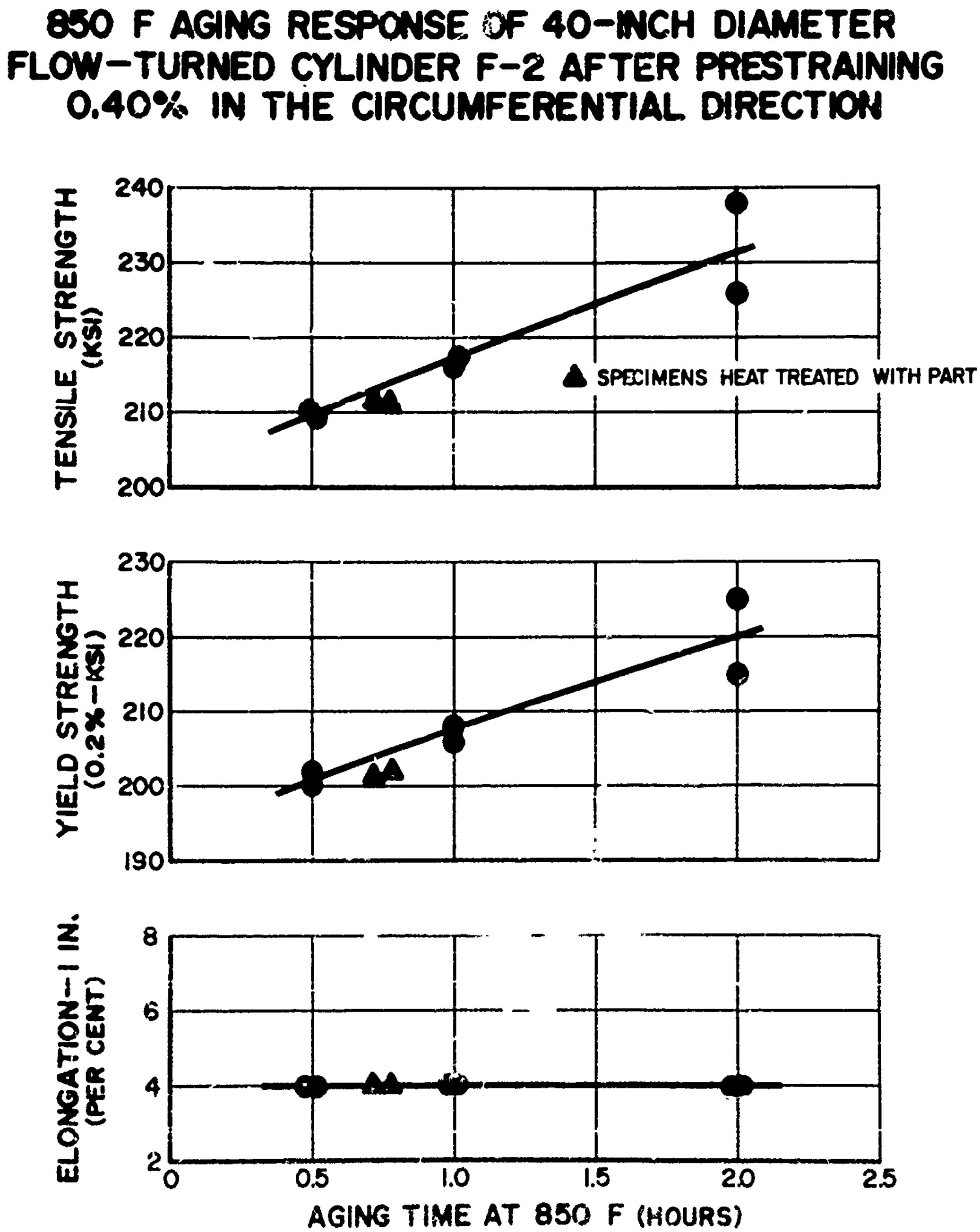
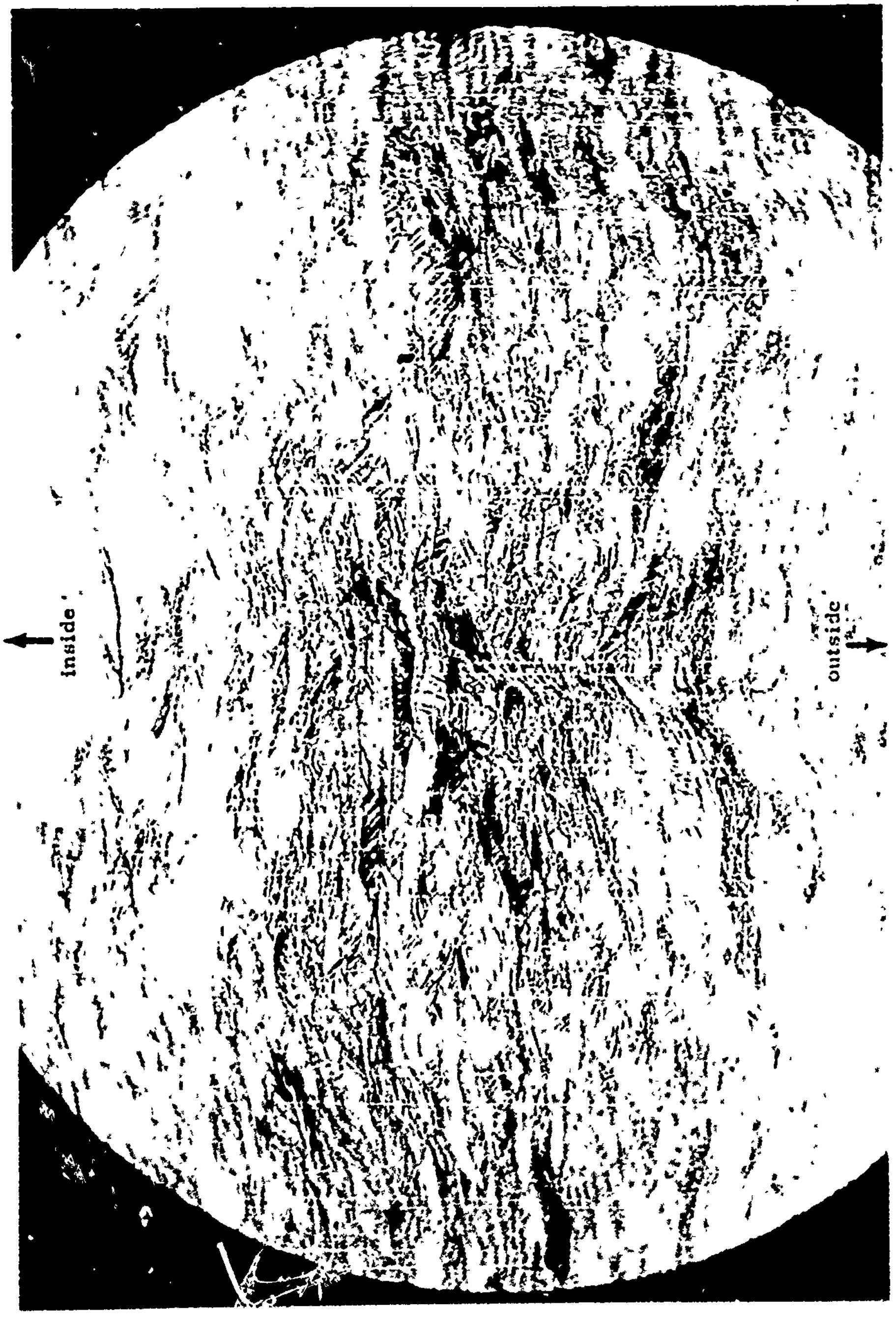
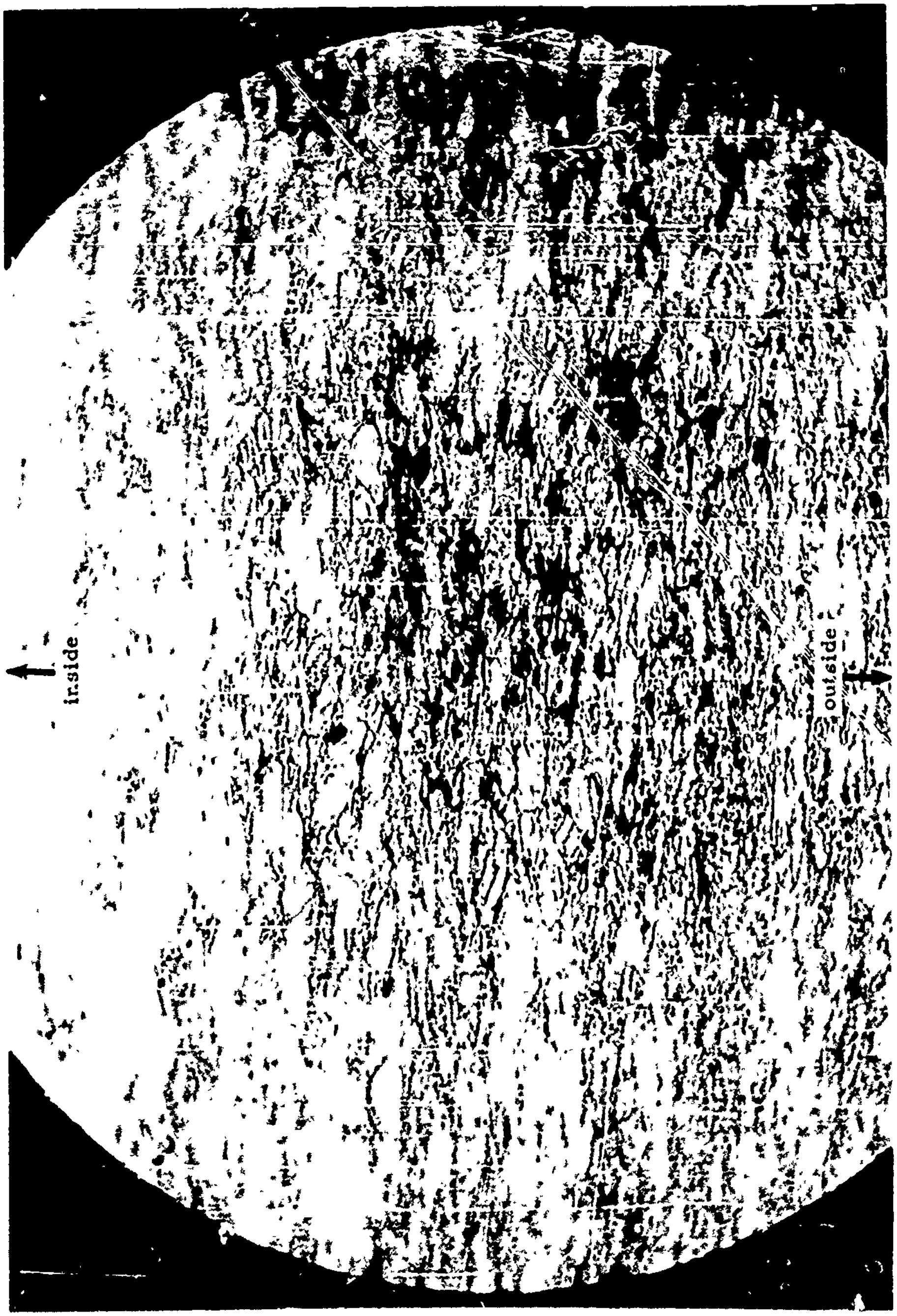

850 F AGING RESPONSE OF 40-INCH DIAMETER
FLOW-TURNED CYLINDER F-2 AFTER PRESTRAINING
0.40% IN THE CIRCUMFERENTIAL DIRECTION
TENSILE STRENGTH
(KSI)
240
230
220
210
200
SPECIMENS HEAT TREATED WITH PART
YIELD STRENGTH
(0.2%-KSI)
230
220
210
200
190
ELONGATION-1 IN.
(PER CENT)
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
AGING TIME AT 850 F (HOURS)

Figure 72



Etchant: 5% HF, 35% HNO_3, 60% H_2O Mag: 100X
Typical Microstructure (Axial View) of 40-Inch Diameter Flow-Turned Cylinder F-7 Stress-Relieved at 850F for One-Half Hour. Note the Numerous Deformation Markings and the Severe Grain Distortion

Figure 73



Etchant: 5% HF, 35% HNO_3, 60% H_2O Mag: 100X
Typical Microstructure (Circumferential View) of 40-Inch Diameter Flow-Turned Cylinder F-7 Stress Relieved at 850°F for One-Half Hour. Note the Numerous Deformation Markings and the Severe Grain Distortion.

Figure 74